GEOPHYSICS

VOL. XXV, NO. 4 AUGUST, 1960

LOGGING ISSUE

G. E. Archie, *Special Editor*

Foreword ..... *G. E. Archie* 731
Duties of a Logging Co-ordinator in an Operating Company ..... *H. M. Johnson* 734
Log Interpretation in Sandstone Reservoirs ..... *M. R. J. Wyllie* 748
Well Logs in Carbonate Reservoirs ..... *L. G. Chombart* 779
Suggestions for Better Electric Log Combinations and Improved Interpretations ..... *H. G. Doll, J. L. Dumanoir and M. Martin* 854
Radioactivity Logging and Its Future Potential ..... *E. S. Mardock* 883
Density Logging ..... *J. J. Pickell and J. G. Heacock* 891
Production Well Logging Techniques ..... *H. L. Bryant* 905
Electrical Analog Approach to Dipmeter Computation ..... *T. H. Braun and G. Y. Wheatley* 928
Collection and Processing of Digitized Acoustic Log Data ..... *R. A. Broding and J. L. Poole* 939

DEPARTMENTS

Discussions and Communications
Discussion on "Photomechanical Method of Frequency Analysis of Seismic Pulses" ..... *Robert C. Moody* 948
Patents 951
Reviews and Publications Received 959
Memorial
Donald Thomas Germain-Jones ..... *T. C. Richards* 967
Contributors 969
Society Round Table
Committees 976
Local Sections 977
Society Affiliations 978
Membership Applications Received 979
Announcements 980
Personal Items 983
Calendar of Meetings 985

Published by the

Society of Exploration Geophysicists

wherever in the world you require

SEISMIC EXPLORATION

. . . whether at the crossroads of the Sahara, in the South American jungles, or on the desolate dunes of Australia, NAMCO is equipped, staffed, and experienced for rendering complete modern seismograph, gravity, magnetometer, core drilling, magnetic recording, and record section services.

For an exploratory discussion contact . . .

namco

INTERNATIONAL, INCORPORATED

LIBYA: Box 677 . . . Tripoli, Libya . . . Cable: Namco-Tripolibya
BOLIVIA: Casilla 1004 . . . Cochabama, Bolivia
U.S.A.: 2345 W. Mockingbird . . . Dallas 35, Texas
telephone FLeetwood 2-2671 . . . Cable: Namco-Daltex

NAMCO international
NATIONAL
McCOLLUM
CONTINENTAL

an affiliation of:
NATIONAL GEOPHYSICAL COMPANY, INC.
P. O. Box 35501 . . DALLAS 35, TEX. . . FLeetwood 2-2671
E. V. McCOLLUM & CO.
515 Thompson Bldg. . . TULSA 3, OKLA. . . LUther 2-3149
CONTINENTAL GEOPHYSICAL CO.
1409 Continental Life Bldg. . . . FORT WORTH 2, TEXAS
[illegible] 9-9291

GEOPHYSICS

Published by the Society of Exploration Geophysicists

EDITORIAL STAFF 1959-1961

NELSON C. STEENLAND, Editor
Geophysical Associates International, Box 22007, Houston 27, Texas

L. L. NETTLETON, Assistant Editor
Geophysical Associates International, Box 22007, Houston 27, Texas

ASSOCIATE EDITORS

G. E. ARCHIE, Well Logging
Shell Development Co., Box 481, Houston 1, Texas

ROBERT J. BEAN, Gravity
Shell Oil Co., Shell Bldg., 1008 W. 6th St., Los Angeles 54, Calif.

ARTHUR A. BRANT, Mining Geophysics
Newmont Exploration Ltd., Briar Ridge Road, R.F.D. 1, Danbury, Conn.

ROBERT JASTROW, Space Physics
National Aeronautics and Space Administration, Goddard Space Flight Center, 8719 Colesville Road, Silver Spring, Maryland

NORMAN R. PATERSON, Magnetics
Hunting Survey Corporation, Ltd., 1450 O'Connor Drive, Toronto 16, Ontario, Canada

O. F. RITZMANN, Patents
The Gulf Companies, Gulf Bldg., Pittsburgh 30, Pennsylvania

EDGAR J. STULKEN, Seismic Field Techniques and Operations
Geophysical Service Inc., Box 35084, Air Lawn Station, Dallas 35, Texas

F. A. VAN MELLE, Seismic Theory and Experimental Seismology
Shell Development Co., Box 481, Houston 1, Texas

JOHN H. HYDEN, Editorial Assistant
P.O. Box 1536, Tulsa 1, Oklahoma

Manuscripts of papers submitted for publication in GEOPHYSICS should be sent directly to the Editor, with the exceptions noted below.

Reviews of geophysical literature published outside of this journal should be sent to the Chairman of the Reviews Committee.

Announcements, news items, and personal items should be sent to the business manager (see next page).

Form of Manuscripts and instructions for its preparation may be found in GEOPHYSICS, v. 19, p. 141-153. Reprints of this style guide may be obtained from the business manager (see next page) upon request.

Responsibility for all statements and opinions made in GEOPHYSICS must be assumed by the respective authors.

Discussions and Letters to the Editor are welcomed by the Editor.

Subscriptions are given to all members of the Society in good standing as part payment for their dues. For non-members and organizations the subscription rate is $10.00 per year in the United States and its possessions and $10.50 per year in all other countries.

Change of Address Notice should be sent to the Business Manager (see next page). Claims for non-receipt must be sent within 3 months of date of publication to be filled gratis.

Single Copy price is $2.50 to members and $3.00 to non-members. For foreign shipment add 20¢ per copy. Subscriptions and single copy orders should be sent to the business manager (see next page).

Microcard copies of all back issues of GEOPHYSICS are available through the business office—prices upon request.

Advertising rates will be furnished by the Business Manager upon request. No advertisements will be accepted for prospecting methods based on hypotheses which are at variance with the accepted principles of physics.

Permission to Copy text material from GEOPHYSICS is limited to one page and is granted on the express condition that reference be made to the source of the material. Larger text excerpts and illustrations from GEOPHYSICS may not be reproduced without written permission of the Editor.

Indexed regularly by Engineering Index, Inc. and by The Applied Science and Technology Index.

Published by George Banta Company, Inc., Menasha, Wisconsin. Issued six times a year in February, April, June, August, October and December. Second-class postage paid at the Post Office at MENASHA, WISCONSIN, under the Act of March 3, 1879. Acceptance for mailing at the special rate of postage provided for in the Act of February 28, 1925, embodied in paragraph 4, Section 538, P. L. & R., authorized March 19, 1941. Copyright 1960 by the Society of Exploration Geophysicists.

Society of Exploration Geophysicists

The *Society of Exploration Geophysicists* had its beginning in 1930 when it was organized in Houston, Texas as the *Society of Petroleum Geophysicists,* the name being changed to its present form in 1936. The Society is dedicated to the advancement of the science of geophysics and the art of geophysical prospecting. Through its journal GEOPHYSICS it supplies a medium for the dissemination of new knowledge in these fields.

BUSINESS OFFICE, Box 1536, Tulsa 1, Oklahoma

COLIN CAMPBELL, *Business Manager*
WILLIAM F. LATTING, JR., *Assistant Business Manager*

COUNCIL

OFFICERS (1959-1960)

T. O. HALL — *President*
General Geophysical Company, 750 Houston Club Bldg., Houston, Texas

FRANK SEARCY — *First Vice-President*
Continental Oil Company, P.O. Drawer 1267, Ponca City, Oklahoma

DEAN WALLING — *Vice-President*
Western Geophysical Co. of America, 523 W. Sixth Street, Los Angeles, California

PHIL P. GABY — *Secretary-Treasurer*
Route 6, Box 203 E, Tucson, Arizona

NELSON C. STEENLAND — *Editor*
Gravity Meter Exploration Company, Box 22007, Houston 27, Texas

E. V. MCCOLLUM — *Past President*
E. V. McCollum & Co., 515 Thompson Building, Tulsa 3, Oklahoma

O. C. CLIFFORD, JR. — *Prior Past President*
The Atlantic Refining Company, P.O. Box 2819, Dallas 21, Texas

DISTRICT REPRESENTATIVES

Ark-La-Tex Geophysical Society
V. W. Teufel (1960)
Bill C. Tucker (1961)

Canadian Society of Exploration Geophysicists
C. J. Chapman (1960)
Norman J. Christie (1961)
Dennis R. Mett (1961)

Casper Geophysical Society
Dupree McGrady (1961)

Coastal Bend Geophysical Society
C. C. Mason (1961)

Cochabamba Geophysical Society
J. Roger Heggblom (1961)

Dallas Geophysical Society
M. S. Hathway (1960)
Wm. C. Woolley (1961)
J. Frank Rollins (1961)

Denver Geophysical Society
Homer Roberts (1960)
Robert C. Kendall (1961)

Geophysical Society of Edmonton
G. D. Garland (1961)

Fort Worth Geophysical Society
C. J. Long (1960)
Paul H. Ledyard (1961)

Four Corners Geophysical Society
Jesse O. Sims (1960)

Geophysical Society of Houston
C. H. Broussard (1960)
S. B. Stewart (1961)
James M. Wilson (1961)

Jackson Geophysical Society
P. P. Gaby (1960)

Montana Geophysical Society
Clyde W. Kerns (1961)

New Mexico Geophysical Society
Robert L. Tucker (1961)

Geophysical Society of Oklahoma City
W. B. Robinson (1960)
Robert H. Peacock (1961)

Pacific Coast Section
M. W. Harding (1960)
R. W. Shoemaker (1960)
F. F. Lambrecht (1961)

Permian Basin Geophysical Society
L. D. Dawson (1960)
R. M. Pinson (1960)
B. F. Owings, Jr. (1961)

Regina Geophysical Society
R. D. Fetherstonhaugh (1961)

Southeastern Geophysical Society
Ronald E. Wright (1960)
Aart DeJong (1961)

Geophysical Society of South Texas
W. Harry Mayne (1961)

Southwest Louisiana Geophysical Society
Jack D. Wallner (1961)

Geophysical Society of Tulsa
Stanley E. Giulio (1960)
Wm. E. Erdahl (1961)
James F. Johnson (1961)

Utah Geophysical Society
L. D. Oster (1961)

Asociacion Venezolana De Geofisica
Dennis C. Meyer (1961)

MODERN ALTIMETER SURVEYS

FIELD INSTRUMENT

AMERICAN PAULIN SYSTEM

MICRO

SURVEYING ALTIMETER

Intervals as close as ONE FOOT

Models available in all ranges.

ENGLISH or METRIC.

Designed for rugged field use under all climatic conditions.

Price in U.S.A.
MICRO MODELS $330
TERRA MODELS $275

WRITE FOR DESCRIPTIVE CATALOG

BETTER ALTIMETER SURVEYS AT LOWER COST

MICRO SURVEYING BAROGRAPH

- CHART READING IMMEDIATELY AVAILABLE
- ACCURATE, SENSITIVE, (Same as our Micro Altimeter)
- EASILY READ
- DEPENDABLE
- LIGHT WEIGHT — EASILY PORTABLE

PRICE IN U.S.A.: $890 complete READY FOR USE

PRECISION RECORDER REPLACES BASE OPERATOR

MADE IN U.S.A.

BASE INSTRUMENT RECORDER

MODEL SMB-5

AMERICAN PAULIN SYSTEM

1524 SOUTH FLOWER STREET • LOS ANGELES 15, CALIFORNIA, U.S.A.

THE WORLD'S LEADING MANUFACTURER OF SURVEYING ALTIMETERS

Hit the Nail on the HEAD

WITH Milligal

ONE IN A MILLION

A potentially productive province may be there, but first you need the assistance of scientific investigation to locate it. Specify E. V. McCollum & Co. Our dependable

gravity surveys

will provide valuable information to you.

E. V. McCOLLUM
515 Thompson Bldg.

CRAIG FERRIS
Ph. LUther 2-3149

TULSA, OKLAHOMA

Foreign Affiliate:
NAMCO International

E. V. McCOLLUM & CO.
WE WEIGH THE EARTH

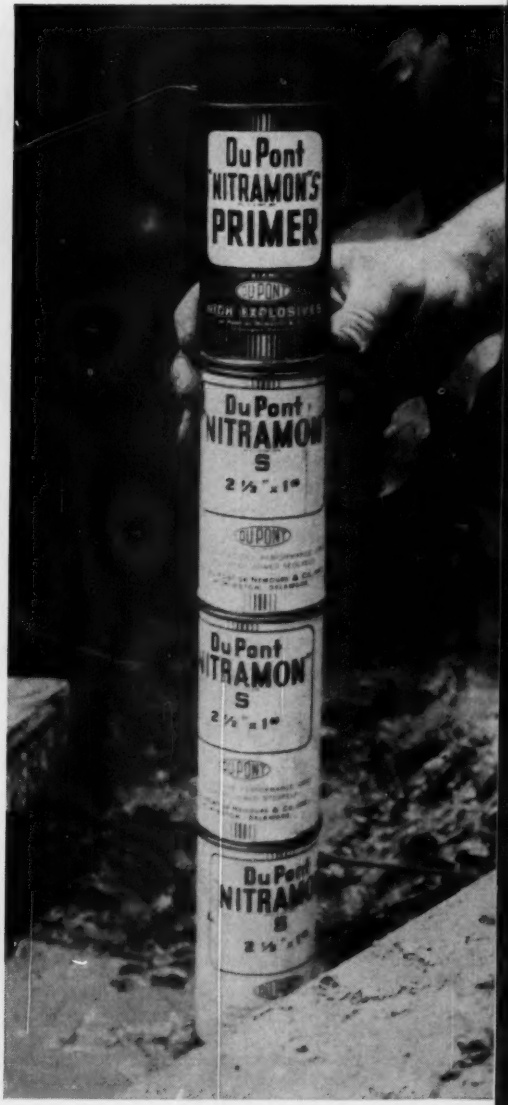
SUSTAINING MEMBERS

For information on Sustaining Membership write to
The Business Manager
Box 1536, Tulsa 1, Oklahoma

EMPIRE GEOPHYSICAL, INC., 6000 Camp Bowie Blvd., Fort Worth, Texas
VARIAN ASSOCIATES, 611 Hansen Way, Palo Alto, California

Du Pont "ELCORD'

Five-foot-long "Elcord" Delay Units screw together with "Nitramon" S charges, to form rigid charges for accurate sequential shooting. They can be easily varied over a wide range of weights, lengths, and velocities.



"Nitramon" S charges and primer attached to the end of "Elcord" Delay Units, completing an elongated charge of predetermined velocity and weight. Each charge, whether of 5 pounds, distributed over 60 feet of hole, or 50 pounds over the same length, is designed to fit a specific problem. Water in this hole will not affect the charge.

Delay Units

can improve the signal-to-noise ratio

Field experience has shown that sequential shooting techniques frequently give a marked improvement in signal-to-noise ratio. In some cases the amount of this improvement has resulted in such economies as substituting a single hole loaded with "Elcord" units for 2, 3 or even 5 hole pattern shots. In addition, the operational aspects of hole location and expensive permitting situations frequently make the use of a single hole desirable even though drilling and charge costs may appear to favor the pattern method.

REDUCED GROUND ROLL: A characteristic feature of sequential shooting is a marked reduction in ground roll. Consequently, "Elcord" charges permit the location of shot holes much closer to dwellings, etc., than is possible with conventional charges.

ACCURATE! "Elcord" Delay Units are accurate to ±3% and are unaffected by borehole conditions such as hardness of the material in which the hole is drilled, the presence or absence of water, etc. When you match velocities with "Elcord" Delay Units, you know exactly what you are doing.

FLEXIBLE! "Elcord" Delay Units are five feet long and can be assembled into charges of any desired length. Greater spacing between the "Nitramon" S sections, in multiples of five feet, can be obtained by screwing two or more units together.

Delays of 0.50, 0.75, 1 and 2 milliseconds provide matched velocities between 2,500 and 10,000 ft./sec. The amount of explosive per delay can be varied from one pound to whatever is wanted merely by changing the number of "Nitramon" S cans between the "Elcord" Delay Units.

PRACTICAL! Designed for use with DuPont "Nitramon" S, "Elcord" Delay Units can be coupled quickly and easily into rigid charges that can be loaded even in badly blocked holes. They're unaffected by water. Can be "slept" indefinitely. Impervious to heat or cold. Highly insensitive to shock and friction. Immune to static electricity. Firing is by means of a "Nitramon" S Primer at the top of the charge. No other primers are necessary, because an "Elcord" Delay Unit will detonate either "Nitramon" S or another unit.

Your DuPont representative can give you full details. Or write: DuPont, Explosives Department, Room 6444, Nemours Building, Wilmington 98, Del.

DU PONT
REG. U. S. PAT. OFF.

DU PONT SEISMIC PRODUCTS

BETTER THINGS FOR BETTER LIVING... *THROUGH CHEMISTRY*

UNITED

Geophysical Corporation

SEISMOGRAPH • GRAVIMETER • MAGNETOMETER

2650 EAST FOOTHILL BOULEVARD, PASADENA, CALIFORNIA • 2920 WESLAYAN, SUITE 203, HOUSTON 27, TEXAS • 422 NORTH MAIN STREET, TULSA, OKLAHOMA • 531 EIGHTH AVENUE WEST, CALGARY, ALBERTA AND 209 MERCANTILE BLDG. EDMONTON, ALBERTA, CANADA • APARTADO 4407 DE CHACOA, CARACAS, VENEZUELA • AV. PRES. VARGAS, 435-19° ANDAR RIO DE JANEIRO, BRAZIL • 194 RUE DE RIVOLI, PARIS 1ER, FRANCE.

Please mention GEOPHYSICS when answering advertisers

DALLAS
MAYHEW
TEXAS

MODEL 200-T

See us in Booth 59 at the Convention.

featuring maximum application versatility . . .

SHOOTING UNIT

Transports explosives, shooting equipment, and water for shot-tamping in seismic operations. Includes racks for loading poles, casing or drill stem.

SHOT-HOLE DRILL

Light-weight rotary type utilizing chain pulldown, double-drum drawworks, 4½ x 5 mud pump. Pump provides uphole water velocity of 300 ft. per minute with a 4" bit.

WATER TANK

All-steel body incorporates water tank, racks to carry drill stem, loading poles, or casing.

TRACTOR-MOUNTED

to permit year-round operations in most areas formerly inaccessible to truck-mounted equipment.

★ Choice of International 350 or Ford 820 tractor. Half-tracks optional.

HOME OFFICE

MAYHEW SUPPLY CO., INC.

4700 SCYENE ROAD • DALLAS, TEXAS

SALES AND SERVICE

CASPER, WYOMING • TULSA, OKLAHOMA • SIDNEY, MONTANA • LUBBOCK, TEXAS • GRAND JUNCTION, COLORADO
EXPLORATION EQUIPMENT CO., INC., HOUSTON, TEXAS

CANADA

SEISMIC SERVICE SUPPLY, LTD., CALGARY AND EDMONTON, ALBERTA

EXPORT

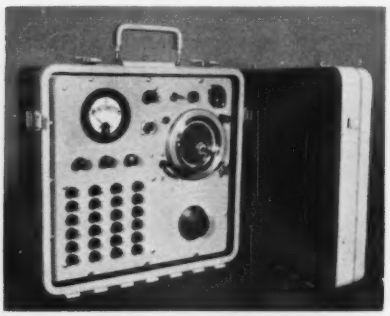
GARDNER-DENVER INT'L, New York, N. Y.

NEW PRODUCTS AND SERVICES

INSTRUMENT CASE

Instrument manufacturers will be interested in the money-saving possibilities of the double-purpose standard instrument cases designed by TA Mfg. Corp. Multiple utility is possible through the removable hinged lids that allow the cases to be used as handsome, aluminum cabinets to permanently house the instruments, in addition to their use as rugged, but lightweight shipping containers.

By allowing the instrument to be mounted directly to the standard case, this TA design idea cuts manufacturing costs and overall weight by eliminating the need for separate enclosures and extra mounting hardware.



The detachable lid serves not only as a dustproof watertight cover for the instrument, but as a storage compartment for cables, spare parts, and instruction manuals.

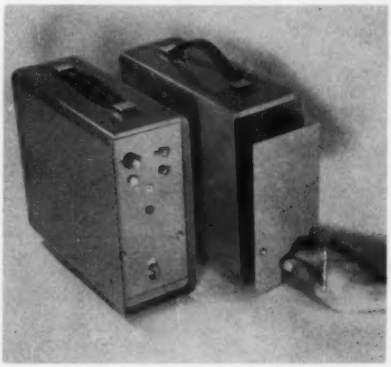
The TA "standard" instrument case line is so called because a diversity of standard lid sizes are available. However, during assembly the depth can be varied to meet almost any requirements—still at proprietary, off-the-shelf prices. In fact, vellums and templates are furnished to instrument manufacturers to allow them to design their products to conform to these standard sizes and thus avoid costly tooling charges for special containers.

TA cases are designed to meet Mil-Std-108C and Mil-T-945A. Special, shock-mounted reinforced aluminum construction is engineered for a combination of strength with minimum weight. Latches, handles and other hardware are mounted on the reinforcing rims to preclude body stress. Cases have Mil-Spec. relief valves that protect contents from pressure changes.

For further information and a free colorful 20-page design manual, write **TA Mfg. Corp., Instrument Case Division, 4607 Alger Street, Los Angeles 39, Calif.**

INSTRUMENT CASES

Designed as an integral part of Alden Plug-in Unit Construction System as a standard, off-the-shelf case for test instruments or as carrying and shipping case for plug-in replacement chassis.



Unique feature is plug-in chassis which is quickly locked in or removed by a half-turn of convenient SERVE-A-UNIT cam lock. Open-sided chassis permits use of snap-in terminal cards mounted in vertical planes of circuitry. All leads are brought to an easily accessible point-of-check that can be graphically identified with circuit legends.

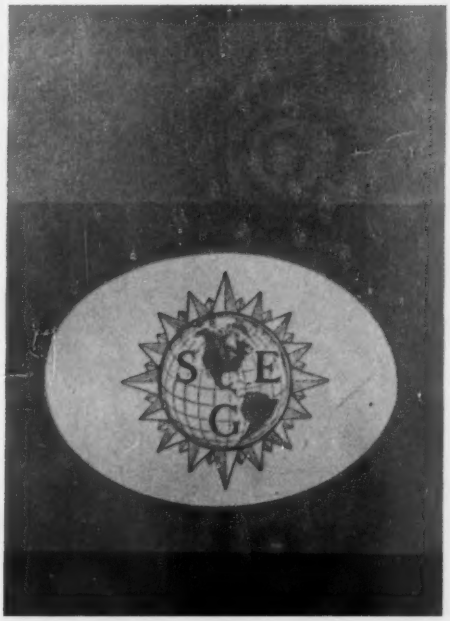
Functional hooded styling protects indicating lights, dials, switches, etc. mounted on front panel. Rugged steel construction; baked enamel finish. Available in 2″, 4″, 8″ widths; 10″ height.

For further information contact **CUSTOMERS' DEPT., ALDEN PRODUCTS COMPANY, IC-155, N. Main St., Brockton, Mass.**

POCKET-SIZED TESTER

Explosive igniters, detonators, primers or squibbs may be checked quickly and safely with a new tester developed by Kin-

(Continued on page 24)



THE SEG CODE OF ETHICS

(SEE DECEMBER, 1959, GEOPHYSICS, PAGE 968 FOR TEXT)

This attractive certificate, printed in gold, blue and black, and suitable for framing, has been prepared by the Society in response to a growing demand.

$2.00 EACH, POSTPAID
MEMBERS ONLY

SEND PAYMENT WITH ORDER TO

SOCIETY OF EXPLORATION GEOPHYSICISTS
BOX 1536 TULSA 1, OKLAHOMA

designs

FROM

ELECTRO-TECH

EVS-2
MINIATURE SEISMIC DETECTOR

M4-E
SEISMIC AMPLIFIER

C-50
GALVANOMETER

DS7-1
FLATBED TAPE RECORDER

MRA-2
MAGNETIC RECORD ANALYZER

ER-102A
RECORDING OSCILLOGRAPH

E-335
CORRECTOR ANALYZER

MFR-1
TRANSISTORIZED FIELD RECORDING SYSTEM

Look to Electro-Tech for Your Seismic Needs

WHETHER YOUR REQUIREMENTS VARY FROM A SINGLE GEOPHONE... TO A FIELD TRANSISTORIZED RECORDER... TO A COMPLETE OFFICE PLAYBACK SYSTEM... ELECTRO-TECHNICAL LABS OFFERS THE MOST COMPLETE LINE OF SEISMIC INSTRUMENTS.

ELECTRO-TECH

CABLE ADDRESS **ELECTROTEX**

ELECTRO-TECHNICAL LABS.
Division of MANDREL INDUSTRIES, INC.
5134 GLENMONT P. O. BOX 13243 HOUSTON 19, TEXAS

OFFICES • U.S.A. Houston • Lafayette • Tulsa EUROPE Paris, France CANADA Calgary, Alberta

GEOPHYSICS ADVERTISERS

ABElektrisk Malmletning 51
Aero Service Corporation 30
Air Photo Supply 62
American Paulin System 3
Askania-Werke 44
Associated Technical Services 22
Atlas Powder Company 15

Bible Geophysical Company 62

Century Geophysical Corporation 25
Continental Geophysical Co. 29

Decca Navigator Co., Ltd. 23
Bert & Ralph Duesing 54
DuPont-Explosives 6–7
DuPont-Photo Products 61

Eastman Kodak Company 37
Electro-Technical Labs 12–13
EAEG 58

George E. Failing Company 54

General Geophysical Company 47
Geophysical Associates International .. 16
Geophysical Service Inc. ..... *4th cover*

Hall-Sears, Inc. 64
Hawthorne 45
Hiller Aircraft Corporation 63

Independent Exploration Company 42
Industrial Photographers 40

Koenig Iron Works 39

Marine Geophysical Services 57
E. V. McCollum & Co. 4
McGraw-Hill 60
Mayhew Supply Company, Inc. 9
Minnesota Mining & Mfg. Co. 33

National Geophysical Co., Inc. ..*2nd cover*

Petty Geophysical Engineering Company 50
PRAKLA 59

Robert H. Ray Company 32
Republic Exploration Co. 53
Rogers Geophysical Companies 35

Schlumberger Well Surveying Corp. .. 41
Seismic Explorations, Inc. 48
Seismograph Service Corp. .....*3rd cover*
Seismos GmbH 36
SEG 5, 52

Texas Instruments, Inc. 26-27, 49
Texas Seismograph Co., Inc. 52
Tidelands Exploration Co. 31

United Geophysical Corporation 8

Varian Associates 55

Wallace & Tiernan, Inc. 28
Western Geophysical Co. 43
John Wiley 56

New Products & Services .....*begins 10*

Professional Directory .....*begins 17*

Please mention GEOPHYSICS when answering advertisers

with blasting caps . . .

it's what's inside that counts

For seismic prospecting, there's no electric blasting cap that beats **STATICMASTER®**.

• IMPROVED STATIC RESISTANCE is demonstrated by exhaustive tests under actual field conditions and by six years service with leading exploration crews. Over 3,000,000 Staticmaster Caps have been sold, with no report of accidental detonation attributed to static!

• DEPENDABILITY tops the field due to exclusive built-in, pretested Atlas electric match. UNIFORMITY in pattern shooting is enhanced because electric match allows bridge wire to be double checked for resistance before and after final cap assembly.

• SAFETY is increased by use of low sensitivity Atlas HNM (hexanitromannite) in primer charge.

• WATER RESISTANCE all the way from cap to top of hole is assured by tough enamel coating on wires, beneath the vinyl insulation...and by genuine rubber plug in cap, hex-crimped to provide 100% watertight seal.

Tell your supplier you want **STATICMASTER** Electric Blasting Caps and Atlas explosives and blasting agents on every trip.

EXPLOSIVES DIVISION

ATLAS POWDER COMPANY

WILMINGTON 99, DELAWARE

Offices in principal cities

Data carefully obtained by GAI seismic surveys, followed by proper analysis, give you the facts upon which to base your decisions. If desired your exploration may be carried out with magnetic recording and section analysis. For a positive reflection of underlying geology based on gravity, magnetic, or seismic surveys anywhere in the world, you can depend on

Geophysical Associates International
3621 West Alabama
Houston 27, Texas, U.S.A.

gai

GMX

Dr. [illegible] Nettleton
[illegible] Jim Shimek
[illegible] Dr. Nelson [illegible] Greenland

VOLUME XXV AUGUST, 1960 NUMBER 4

GEOPHYSICS

FOREWORD

G. E. ARCHIE*

A symposium on well logging, arranged by the Program Chairman, Mr. T. H Braun, with the assistance of Mr. H. M. Johnson, was held at the 29th Annual Meeting of the Society of Exploration Geophysicists, Los Angeles, California, November 9–12, 1959.

A number of experts discussed various aspects of well logging; and their contributions, as well as additional papers on the subject, are presented in this issue. The collection is of interest to the geophysicist who wishes to become better acquainted with current thinking on the subject. Items include examples of staff organization, discussion of physicochemical properties of rocks, general interpretation of sandstone and limestone conditions, and descriptions of specific types of surveys. The issue is also of interest to geophysicists, geologists, and engineers specializing in well log interpretation because it reviews recent advances in this field, including the usefulness of logging tools for well completion and workover, a subject which has been given little attention.

A brief statement regarding the scope of this subject may be of interest.

Interpretation of well surveys is based on physicochemical and petrological relationships of rocks and contained fluids, including hydrocarbons; the subject is therefore referred to as *petrophysics*. Physiochemical properties of rocks and fluids involve all the basic science disciplines including physical, organic and inorganic chemistry; classical and atomic physics; and mathematics. Further, the heterogeneity of rocks and their contained pore and fluid structure require that many empirical data be co-ordinated with the theory to arrive at useful relations. Research into these relationships therefore necessitates a knowledge of geology. It would be an infinite task to make numerous types of measurements on all variations of each type of rock and fluid distribution. It is therefore necessary to work within a geologic framework in determining or discovering a new relationship.

Determining the geological significance of physicochemical properties is basic in petrophysics. In practice, however, the measurements have to be made in a borehole filled with fluid where, further, the mud filtrate has contaminated the

* Shell Development Co.

permeable formations. Interpretation must also take into account the effects of variations in borehole size, condition of the filtrate-invaded zone, and the effects of adjoining layers. At depths as great as three miles the physical conditions of rocks and their contained fluids are measured indirectly by means of their electrical, radioactive, and acoustical properties. It is a problem to make a good instrument to record these properties and to telemeter the data to the surface.

Much subsurface information required for exploration drilling and for the production of oil comes from well logs. Since the subject of petrophysics encompasses a wide range of problems, some companies have found it advisable to create a petrophysical organization. Such an organization is discussed by H. M. Johnson. The sedimentary geologist divides his provinces into sandstones and carbonates; the petrophysicist finds it convenient to so divide his interpretation problem. Wyllie discusses the former and Chombart, the latter.

Logging in clastic formations is reviewed by M. R. J. WYLLIE, who has, himself, made significant contributions. He describes the most suitable tools for sandstone evaluation, pointing out the importance and usefulness of the invaded zone. Assumptions often used in sandstone interpretations, particularly in the difficult and not fully understood case of shaly sands, are discussed; and areas for future research are suggested.

The complex subject of carbonate interpretation is covered comprehensively by L. G. Chombart who undertakes a most complete summary, starting with presently known fundamental concepts of the physiochemical properties of porous carbonates and building a background for what may be called a "total" approach to evaluation of these heterogeneous reservoirs. This approach considers the relationship between pore size distribution, capillarity, and saturation predicted from cores in key wells and from drill cuttings in remaining wells, all co-ordinated statistically with well surveys to arrive at the most probable evaluation.

New approaches to electrical methods of logging, the only systems that can estimate the hydrocarbon saturation, are discussed by H. G. DOLL, J. L. DUMANOIR, and M. MARTIN. The new methods of induction and focus systems have high vertical resolution and are relatively unaffected by the mud column. Thus, the interpretation of thinner layers can be approached more quantitatively, both in the invaded zone and in the uncontaminated formation.

E. S. MARDOCK, in his paper on Radioactivity Logging and its future potential, indicates that the future of induced radioactivity logs to obtain quantitative information will depend on industry's ability to detect singularly thermal, epithermal, or fast neutrons or else neutron induced gamma rays. Many logs today record a combination of these.

A concise review of density logging is presented by J. J. PICKELL and J. G. HEACOCK, including a brief discussion of the gamma ray theory, various calibration curves, comparison of density-log and core data, and comments on interpretation.

HARVEY L. BRYANT describes another use for well surveys, i.e., analysis of

older cased wells. This is becoming important with the increase in secondary recovery and recompletions. Various techniques are summarized for aiding well completion, repair, and treatment. Logs indicating the source, quantity, and composition of fluid entering the well are discussed. Of particular interest is the use of nuclear logs used in flowing wells to detect points of gas and water entry and gas/oil and oil/water ratios.

Valuable tools which can aid in solving problems are also presented. These tools allow computational procedures to be performed easily whereas previously they were tedious. T. H. BRAUN and G. Y. WHEATLEY describe an electrical analog useful in calculating the dip and strike from continuous dipmeter surveys. R. A. BRODING and J. L. POOLE describe the collection and processing of acoustic log data and indicate that future logs will probably be recorded in digital as well as analog form.

GEOPHYSICS, VOL. XXV, NO. 4 (AUGUST, 1960), PP. 734-747, 7 FIGS.

DUTIES OF A LOGGING CO-ORDINATOR IN AN OPERATING COMPANY*

DR. HAMILTON M. JOHNSON†

ABSTRACT

A well logging co-ordinator for an operating oil company is often considered to be only a "log analyst" but quantitative log analysis should constitute only a small part of his duties. Associated with the actual analysis are the compilation and preparation of auxiliary reservoir data, field research and evaluation of new tools and methods designed to solve problems of particular areas and conditions, the co-ordination of logging programs with drilling programs and the development of interpretation techniques.

For the company to achieve the most efficient use of its logging dollar, the co-ordinator must maintain a constant check on log quality, conduct schools on formation evaluation for field personnel and serve as an advisor on unitization committees.

It is helpful to him in realizing this program to have a logging research group within the overall research effort of the operating company to aid him in specific problems and to help him keep abreast of industry-wide research.

INTRODUCTION

The use of electric logging, introduced commercially in 1929 by Conrad and Marcel Schlumberger, initiated an entirely new era in the evaluation of formations cut by rotary drilling. The obvious advantages of accurate formation depths, relative ease of subsurface correlation, and a qualitative estimate of fluid saturation led to its almost immediate acceptance. The success of the electric log spurred interest in other types of logs based on other physical and chemical parameters and resulted in the wide diversity of logs currently available, including focused and non-focused, centered and wall-contacting, radioactive and sonic. There are also the associated tools including dipmeter, sidewall coring, fluid sampler, and others.

Geologists and petroleum engineers use these tools and logs every day in their work but this use has been largely qualitative. As is true of many other products of the mechanical skill of man, the first principles are so simple that many users stop there and never learn to appreciate either the refinements possible or the dangers which lurk in those cases for which the simplified assumptions do not apply.

An intelligent use of any type of log recorded in a borehole requires a thorough knowledge of the effect of the many variable conditions in and around the borehole. Recognition of these variables has led to the development of many of the new logging tools, each of which is designed for some specific purpose. To use these new tools to the best advantage, it is necessary to understand the purpose of the tool, its limitations and degree of success in fulfilling this purpose, and the

* Presented at the 29th Annual International Meeting of the Society, Los Angeles, California, November 10, 1959, manuscript received by the Editor December 4, 1959.

† Tulane University and Jersey Production Research Company.

economic feasibility of its use. The number and complexity of logging methods introduced, the wide application of all methods in exploration, development, completion, workover, and secondary recovery techniques, and the cost of these operations has led to a new technical position in many companies; this position is that of the "logging co-ordinator."

A well logging co-ordinator for an operating company is often considered to be only a "log analyst," and his potential usefulness to the company is evaluated only in this regard. The reasons previously stated which forced the creation of this position and the enumeration of job phases which follow indicate that log

OPERATIONS

- Analyses
- Data Compilation
- Service Liaison
- Drilling Programs
- Unitization
- Quality Control

RESEARCH

- Literature
- Specified Problems
- Economics
- Company Sponsored Research

EDUCATION

- Primary
- Advanced

FIG. 1. Division of duties of a logging co-ordinator.

analysis should be only a small portion of the duties involved. These duties have been arbitrarily placed into 11 subdivisions, although all are interdependent.

As shown in Figure 1, these duties may be roughly separated into three groups; those dealing with applications within the operating districts and divisions, applied research leading to better interpretation and solution of operating problems, and teaching operating personnel to understand and use logging methods more profitably. It is probable that the number of building blocks within each of these groups, i.e., six, four, and two respectively, represents the relative importance of each group within the total duties of the co-ordinator.

Make Qualitative and Quantitative Analyses of Logs

Appraisal of formation and reservoir properties from a study of logs can be divided into two phases, i.e., qualitative and quantitative, on a basis of numercial approach. Under qualitative should be included lithology, gradational changes in lithology, subsurface correlation, formational tops, bed thickness, and general estimations of fluid content and permeability. However, this is the stage where

interpretation (and use of the log) often stops. An analogous case would be buying an automobile capable of traveling at 150 mph on open highway and then using it only to drive to and from the office. This is not to imply that the maximum speed should always be used; it simply refers to the fact that there is no sense in paying for a great deal of horsepower which will never be used. For example, the focused contact log is designed to measure R_{xo} so that a computation of formation porosity may be made. If there is no intent to make this calculation, then the use of this particular log is seldom economically justifiable.

Quantitative analyses involve calculations using formulae interrelating various reservoir properties and logging measurements. These analyses include

$$F = R_o / R_w = 1/\phi^m$$

$$S_w = \sqrt[n]{R_o / R_t}$$

$$E_c = -K \log_{10} R_{mf} / R_w$$

$$\Delta t = \phi / V_f + (1 - \phi) / V_m$$

FIG. 2. Basic equations for quantitative analysis.

determination of interstititial water resistivity, porosity, and percentage water saturation.

In Figure 2 are shown some basic equations of quantitative log interpretation. The first three equations consider electrical properties of the formations and the fourth equation relates porosity to elastic properties of the reservoir. Each of these, plus others which are specialized variations of these, are discussed by the authors within this symposium.

Even with this information, a knowledge of the critical water saturation is necessary in order to determine whether clean oil, water-cut oil, or water will be produced. A permeability may be calculated from these reservoir data, but the assumptions have been too simplified and the resulting answer does not yet have an accuracy approaching that of the other calculated reservoir properties.

The key values which are needed for a study of fluid saturation are the resistivity of the uncontaminated formation (R_t) and the resistivity which that formation would have if completely saturated with water (R_o). However, there are many other factors to be considered before these values may be determined. Some of the other factors are relatively constant for a given reservoir. These factors are discussed in the following paragraphs.

Compile and Prepare Data Leading to Improve Interpretation of Logs in Areas of Company Operation

Some of the data which should be compiled in this improvement effort are schematically shown in Figure 3. Particularly important are compilations of interstitial water resistivities (R_w) for each reservoir of each operations area; values for K, the "unconstant constant" of the S.P. equation; values for m, the cementation factor in the porosity-formation factor relationship; and values for n, the Archie saturation exponent.

Figure 3 shows schematically how a knowledge of K and measured values of S.P. and R_{mf} may lead to a calculated value for R_w under conditions which often

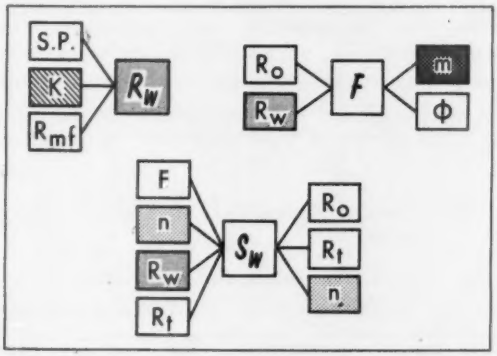


FIG. 3. Schematic representation of quantitative relationships.

may be assumed to exist. Then a value of R_w, either this calculated one or one measured from an actual fluid sample, plus an occasionally determinable value of R_o may lead to F. This, in turn, if a value for m is known from core analysis or experience will yield percentage porosity which is one of the reservoir properties desired. Using these values of F and R_w, a measured and corrected value of R_t, and an empirically determined value of n, a calculation for S_w may be made. Or, using the values of R_o, R_t, and the previously determined value of n, the calculation for S_w may be made. This is percentage water saturation, another of the desired reservoir properties.

Values for R_w for each reservoir in each operating area are of extreme importance, being included in each of the relationships shown. If at all possible, these should be actual measurements of liquid samples of the formation water recovered in an uncontaminated portion of a drill-stem test or as break-out on a production run. They may also be derived resistivities calculated by the Dunlap relationship on chemical analyses of the waters. It is probable that this compilation of water resistivities is the most important single tool to a log analyst.

The lack of such a tabulation seriously restricts the possible choices of mud program in drilling wildcat wells, because of the necessity of obtaining a good S.P. curve for calculation of this property.

Values for K may be computed and tabulated for each reservoir by working the S.P. equation backward when all other values are known. This value depends on lithology and temperature but must be determined empirically.

Values for m and n are also determined empirically by solving for them in the equations given, when all other values have been determined from core analysis. Since these other values are usually not known, compilations of m and n values can be extremely useful.

Of equal importance in the final determination of whether a given zone will be commercially productive is a knowledge of the critical water saturation. This must be determined from an empirical study relating core-measured water saturations to production records. Such studies should be made for all reservoirs of an operating area. Theoretical approaches to a solution of this problem have been devised, but because of the number of variables contained in these approaches and the heterogeneity of most reservoirs, the empirical tabulation is still the best.

Follow Literature on Formation Evaluation and Try New Methods to Evaluate Usefulness

This is an important and never-ending function. The highly technical reports of basic developments are published in the technical society journals while articles giving specific applications and case histories are more often published in the trade journals. The volume of these latter articles is evidence of the great interest in logging but it may have tended to make some users of logs careless in the application of logging methods, for the popular articles necessarily underplay the assumptions required and the inaccuracies involved.

Maintain Liaison with Service Companies

Efficiency in field operations is increased if an operating company has someone at some level above the local districts who can act as a clearinghouse for any major inquiries about service company methods and prices, as well as investigating reports of unsatisfactory logs or services.

This action should not replace a very close association between men in the operating districts and the local service company districts; the need for great co-operation here cannot be overemphasized. However, when this climate occationally deteriorates or when questions of regional company policy in regard to methods, services, or prices arise, then the use of a co-ordinator in performing liaison may complement the efforts of the operating personnel of different districts in achieving a more widespread change than would otherwise be possible.

Study Particular Problems Affecting Company Operations (HGOR, Fluid Losses, Water Encroachment, Etc.) and Try to Devise Logging Methods to Aid in Their Solution

Most of the logging tools have been designed for formation evaluation in open hole and the determination of particular reservoir properties rather than for solution of drilling or production problems. This equipment can measure many various physical properties such as electrical resistance and conductivity, radioactivity, gamma-ray absorption, thermal changes, elasticity, induced gamma rays from neutron bombardment, and even borehole rugosity under downhole conditions of temperature and pressure. It seems reasonable that such tools

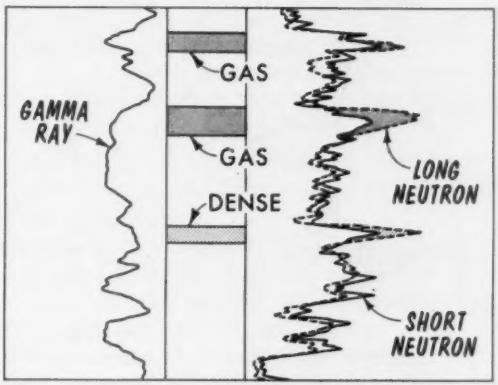


FIG. 4. Multi-spaced neutron log.

can be adapted for uses other than those originally considered. Therefore, very special methods of use and interpretation of the conventional tools must be devised for these different purposes. Such methods include, among others, the flowing neutron log, the flowing density log, the multi-spaced neutron, the resistivity interface, and use of isotopes. These "production uses" of logging methods will be discussed at this symposium by Mr. H. L. Bryant, who originated several of them for the Creole Petroleum Corporation; they include changes in the conditions at time of logging with conventional tools or slight modifications in the existing instruments. Empirical interpretation methods have been developed for immediate field use and these have then been further refined by theoretical analyses.

Figure 4 shows an example of the multi-spaced neutron log which was developed in the field in Venezuela in an effort to locate gas-cap accumulations.

This has been satisfactory in some areas in which dry gas is found and has resulted in greatly reduced gas/oil ratios at the time of initial completion.

Other such problems might be detection of porosity in a fractured zone, subsidence during the producing life of a field, and effects of gas or water injection as a secondary recovery method.

Work with Drilling and Petroleum Engineers in the Preparation of Drilling Programs, Particularly in Co-ordinating the Logging Program with the Mud Program

This is sort of an "ounce of prevention" program wherein a logging co-ordinator is extremely valuable in acting as liaison between those interested primarily

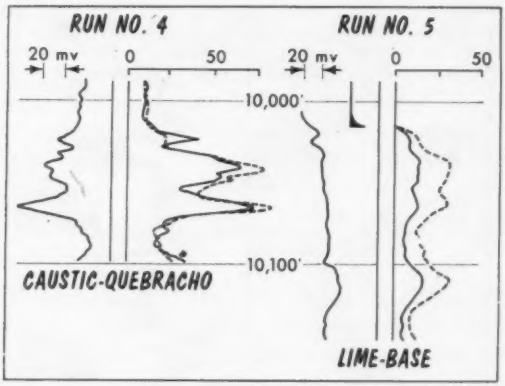


FIG. 5. Effect of drilling mud on electric log.

in getting a hole down and those interested primarily in evaluation of the formations cut by the hole.

Drilling muds have necessarily become more and more complex in nature because of the increased temperatures and pressures found in deeper drilling. The mud, cake, and filtrate resistivities are related to those complexities in various ways. Some of these relationships are still unknown. Since electrical logs are recorded with a downhole system of electrodes surrounded by the drilling fluid, and since the results are greatly affected by these characteristic resistivities, the importance of a detailed knowledge of the effects of mud on logs is obvious.

The field has become crowded with competitive mud products, designed to fulfill almost any need—but all are considered by the drilling engineer for their aid in promoting efficient drilling operations while very little attention has been directed to their effect on formation evaluation. The completely destructive effect of a particular mud on the conventional electric log is shown in Figure 5. In this example, Run n. 4 was a conventional electric log recorded in a freshwater mud having a resistivity of 3.1 ohm-m at 100°F. A sand between 10,000

ft and 10,100 ft was indicated to be potentially oil-bearing, which was confirmed by other tests. But when casing was set at the top of this sand, the mud changed to a low-resistivity lime-base mud and drilling continued, the following run with the conventional electric log failed to indicate that this sand even existed. This should focus attention upon the effect of various muds upon the methods to be used in formation evaluation.

It is possible that major economic savings may be realized by carefully integrating the logging program with the remainder of the program, at the time of preparation of the overall drilling program for either a single well or development of an area. Multiple surveys in an indivividual well may be eliminated or reduced in number, and the use of logs which simply yield duplicating information may be recognized and curtailed. Also an awareness of price and value to be received from each logging method is maintained, and new developments are more quickly introduced into the programming.

Work with Company and Intercompany Committees on Unitization to Recommend Methods of Log Interpretation for Reservoir Studies

Many of the problems which arise in reservoir studies, particularly in those studies involving more than a single company, involve the use of logging methods and interpretation in their solution.

Such physical properties of the reservoir as sand thickness, percentage of shale within the producing horizon, porosity, and percentage water saturation may all be estimated by logging methods. Even the permeability of sandstones can often be very roughly estimated from electric logs.

For example, there are at least six methods of making a "sand count." These include using (1) a manual count from the S.P. curve of the electric log, (2) a manual count from the gamma-ray curve, (3) positive separation on the micrologg, (4) the S.P. deflection beyond some arbitrary value, (5) resistivity deflections on the short normal resistivity curve (in a sand-shale region only) and (6) the planimetered area under the S.P. curve. All of these have been used at one time or another in reservoir studies. Others are now becoming available with density logs, velocity logs, focused wall-contact logs, etc. Given such a multiplicity of choices and the always present assumption that any specific method will favor one company over another, the presence of a person well versed in logging may be invaluable to his company.

Review Economics of Logging to be Able to Insure That His Company Receives the Maximum Information for Least Money

There are many ways in which an economically optimum use of logging methods may be achieved. All involve several specific features, including: (a) a knowledge of the exact type of information which is desired by the geologist or engineer; (b) a knowledge of the exact type of information which may be obtained through use of each logging method; (c) a thorough knowledge of the pricing

schedules of all service companies operating in the area . . . and a knowledge of relative prices of these service companies in their worldwide operations; and (d) excellent relationships with the service companies so that all unwritten special advantages and charge arrangements which may be implied (but not spelled out) in their price schedules are understood and utilized to the fullest extent.

A comparison of the prices of one of the major logging companies for various continuous logs is shown in Figure 6. This is based on a first run at 10,000 ft for

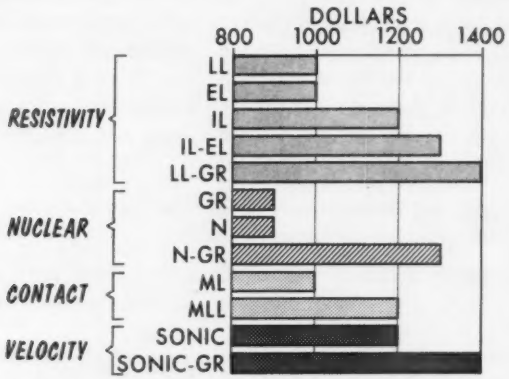


FIG. 6. Logging cost comparisons.

each type of log, with no set-up charge assessed. As shown, there are five logs or logging combinations which may be used in an effort to determine the true formation resistivity. They are designed for optimum application under different lithological and borehole conditions. The logging prices vary widely, so it is important that the cheapest log which gives adequate results under these environmental conditions should be used. The specific knowledge of the logging co-ordinator acting for his company is valuable here; it is unreasonable to expect a salesman for a service company to consistently recommend a cheaper log which is adequate when there is a high priced one which may or may not be somewhat better.

One important point that should be remembered cost-wise in an analysis of logging methods vs scheduled prices is the cost of rig time. It is not true that all companies record the same logs at the same speed or even with the same number of trips in the hole. The cost of the rig-time involved in an extra trip may much more than offset the advantage of a slightly lower logging price per ft.

Another important point which should be emphasized with regard to cost reduction is that while competition between various service companies is healthy and should be encouraged, those companies having good records for research, development, quality and co-operation should be favored.

Review All logs in Order to Maintain Quality Control

The extremely rapid expansion of the petroleum producing industry in the years since World War II, and the correspondingly great expansion by the service companies during this period (both in personnel and in the number and type of logs recorded), has meant that personnel has been added faster than a thorough understanding of the tools employed could be imparted. This has been equally true of both the operating companies and the service companies. Because of this

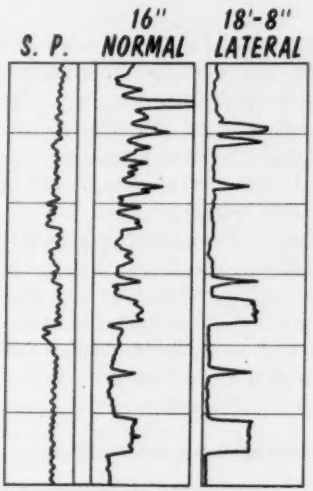


FIG. 7. Defective electric log.

the quality of logging records is not as high as it should be. The logging engineers may run poor logs and never recognize the fact; and the geologists may accept poor logs and likewise not realize it.

An example of such a defective log is shown in Figure 7. This is a conventional electric log recorded with short circuiting in the head. There also appears to be the effect of a magnetized drum superimposed on the S.P. curve. The perfectly symmetrical square shape of the lateral resistivity curve is positive evidence of a very serious defect. Nevertheless, this log was recorded and its defective nature was not noticed by either the service company or the operating company. Thus, it is possible for such things to occur.

Recognition of poor or defective logs is a subject which should be taught by the logging co-ordinator to all field personnel. However, in addition to such instruction, the co-ordinator should examine all logs (both exploratory and development) in regard to logging quality. Inferior logs should be reported immediately to the service company involved, and further attention should be given to see that equipment repairs are made and mistakes not repeated.

The interpretation cannot possibly be better than the quality of the log. The greatest loss in connection with a defective log is not the cost of the log involved (a charge often cancelled by the service company) but rather the loss of desired information which can never be obtained after casing has been set or a hole lost or abandoned. Thus recognition of a poor log while still at the well site at the time of logging is of paramount importance.

Conduct Schools for Formation Evaluation at Regular Intervals for Geologists and Petroleum Engineers

The number of logging methods, as well as logging companies, which are now used in operations requires that each man in an operating capacity know the comparable information obtained from the logs, the comparable quality of logging equipment, and the quality of service offered by the various companies. He must be familiar with price schedules, research projects underway, analysis of borehole conditions, etc. In other words, he should be a logging "expert" at least for the area in which he is working.

Because of the complexity of the total logging field, the schools should be divided into "primary" for new employees with no prior field experience and "secondary" for advanced training of men having some field experience. These schools should be designed to aid the operating personnel in obtaining maximum quality in the logs recorded, in obtaining maximum information from these logs by means of a more thorough qualitative and quantitative study, and in obtaining all of these as economically as possible.

Maintain Close Contact with Logging Research Efforts

Since the logging co-ordinator is constantly concerned with making formation evaluations and with applied research on improving the techniques employed in these evaluations, he must follow all logging research efforts as closely as possible. This will not only reduce duplication but will also aid in achieving better results in less time and at less cost.

In this regard, inclusion of a logging research group within the overall research effort of the operating company or within the corporate framework of a group of affiliated companies is of great value. The research group can keep the operating company informed of all new developments made by the research group itself, by other affiliates, by service companies and by competitors. The co-ordinator can inform all affiliates, through the research group, of improvements in logging techniques developed within his own company. He can also effectively bring key problems to the attention of the research group. The co-ordinator should call on the research group for any aid that may complement or supplement his duties as outlined above.

CONCLUSIONS

Through all of the previous discussion, it is seen that the fundamental job of the co-ordinator is to insure that his company obtains the most value from

well logging at the least cost. He does this by technical analyses made personally, by personal research to improve interpretation methods, by advising other departments in regard to technical aspects of logging uses, by continuously reviewing economics of logging, by teaching other personnel to do all of the above on a more localized scale, and by co-operating in and with the overall company research effort.

ACKNOWLEDGMENT

The author desires to express his appreciation to the Creole Petroleum Corporation, Caracas, Venezuela, in which company he served as Well Logging Co-ordinator for their permission for the presentation of this paper.

He also desires to thank Tulane University, which he currently serves as Professor of Geology and Geophysics, and the Jersery Production Research Company, with whom he is associated as a Consultant in Logging Research, for their permission to present this paper.

The assistance and encouragement of Drs. David A. White and Kenneth C. Crumrine of the Jersey Production Research Company in the development and organization of this paper have been of great value to the author, as was the co-operation of the personnel of the operating districts of Creole in developing these ideas.

REFERENCES

Archie, G. E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Petr. Tech., A.I.M.E., T.P. 1422, v. 5, n. 1.

Archie, G. E., 1947, Electrical resistivity an aid in core-analysis interpretation: Bull. A.A.P.G., v. 31, p. 350–366.

Bailey, B. H., Bryant, H. L., and Powell, N. L., 1957, Spot those gas zones with neutron logging: Oil and Gas Journ., p. 368–370.

Boucher, F. G., Hildebrandt, A. B., and Hagen, H. B., 1950, New dip logging method: Bull. A.A.P.G., v. 34, p. 2007–2026.

Caldwell, R. L. and Sipple, R. F., 1958, New developments in radioactive well logging research: Bull. A.A.P.G., v. 42, p. 159–172.

Campbell, Orton E., 1946, Principal uses of fluorologs: Oil Weekly, v. 124, p. 41–42, 44–45.

Davis, C. R., 1957, Water resistivity determination in the Denver Basin: presented First Formation Evaluation Symposium, Canadian Well Logging Society, Calgary, Alberta.

de Chambrier, Pierre, 1953, The microlog continuous dipmeter: Geophysics, v. 18, p. 929–951.

Doll, H. G., 1943, The S. P. dipmeter: Petr. Tech., A.I.M.E., T.P., 1547, v. 6, n. 1, p. 1–10.

——— 1949, Introduction to induction logging and application to logging of wells drilled with oil base mud: Journ. Petr. Tech., A.I.M.E., T.P. 2641, v. 1, n. 6, p. 148–162.

——— 1950, The microlog—a new electrical logging method for detailed determinations of permeable beds: Petr. Transactions, A.I.M.E., v. 189.

——— 1953, The microlaterolog: Journ. Petr. Tech., A.I.M.E., T.P. 3492, v. 5, n. 1, p. 17–32.

——— and Martin, M., 1954, How to use electric log data to determine maximum producible oil index in a formation: Oil and Gas Journ.

——— and Schwede, H. F., 1947, Radioactive markers in oil-field practice: Petr. Tech., A.I.M.E., T.P., 2261, v. 10, n. 5.

Dunlap, H. F., and Hawthorne, H. R., 1951, The calculation of water resistivities from chemical analysis: Journ. Petr. Tech., A.I.M.E., v. 3, n. 3.

Forsyth, Val L., 1942, Accuracy of depth measurements is influenced by many factors: Tomorrow's Tools—Today, v. 8, n. 2, p. 4.

Grosmangin, M., and Walker, E. B., 1957, Gas detection by dual-spacing neutron logs in the Greater Oficina area, Venezuela: Journ. Petr. Tech., A.I.M.E., T.P. 4586, v. 9, n. 5, p. 140–147.

Guyod, Hubert, 1937, Photo-electric cell is applied in locating water intrusions: Oil and Gas Journ., v. 36, p. 50.

——— Aug. 7, 1944, Review of well logging methods: Oil Weekly.

Howell, Lynn G., and Frosch, Alex, 1939, Gamma ray well logging: Geophysics, v. 4, p. 106–114.

Johnson, Hamilton M., 1958, A geologist's view of drilling muds: Third Annual Petroleum Conference on Well Logging Interpretations, McMurry College, Abilene, Texas.

——— 1958, The importance of accuracy in basic measurement for electric log analysis: Third Annual Petroleum Conference on Well Logging Interpretations, McMurry College, Abilene, Texas.

Jones, Park J., 1951, Electric log resistivity, porosity, and water saturation for clean and shaly sandstones: World Oil, v. 132, n. 2.

Kean, C. H., and Tullos, F. N., 1948, Acoustic impedance logging: Oil and Gas Journ., v. 47, p. 95.

Keller, G. V., 1949, An improved electrode system for use in electric logging: Producer's Monthly, v. 14, n. 9, p. 13–16.

Kokesh, Frank P., 1952, The development of a new method of seismic velocity determination: Geophysics, v. 17, p. 560–574.

Lebourg, M., Fields, R. Q., and Doh, C. A., 1957, A method of formation testing on logging cable: Journ. Petr. Tech., A.I.M.E., T.P. 4635, v. 9, n. 9, p. 260–267.

Lenhard, P. J., and Cecil, C. J., 1945, Application of the electric pilot to well completions, acidizing, and production problems in the Permian Basin: Petr. Tech., A.I.M.E., T.P. 1759, v. 8.

Leonardon, E. G., 1936, Thermometric measurements in drill holes: Geophysics, v. 1, p. 115–126.

——— and McCann, D. C., 1939, Exploring drill holes by sample taking bullets: Petr. Tech., A.I.M.E., T.P. 1062, v. 2, n. 2.

Martin, M., and Dumanoir, J. L., 1956, Determining true resistivity: World Oil, v. 143, n. 1.

——— Murray, G. H., and Gillingham, W. J., 1938, Determination of the potential productivity of oil-bearing formations by resistivity measurements: Geophysics, v. 3, p. 258–272.

Miner, Keith H., 1944, Checking downhole measurements by collar location: Tomorrow's Tools—Today, v. 10, n. 3, p. 32–34.

Mounce, W. D., Hubbard, C. L., Charske, C. J., and Kuppers, J. P., 1951, Seismic velocity logging: presented SEG annual meeting, Dallas, Texas, Nov. 20, 1951.

Olson, C. C., 1949, Interpretation and use of drill-stem testing and bottom hole pressures: University of Oklahoma Subsurface Logging Symposium, p. 67–69.

Parsons, C. P., 1942, Caliper logging: Petr. Tech., A.I.M.E., T.P. 1474, v. 5, n. 3.

Pontecorvo, Bruno, 1941, Neutron well logging: Oil and Gas Journ., v. 40, p. 32–33.

Sanders, T. P., 1937, Drilling time curves for analyzing pay strata: Oil and Gas Journ., v. 35, n. 36, p. 43.

Schlumberger Well Surveying Corp., 1957, Scheduled prices effective Jan. 23, 1957 in most of the U.S.A.

Schlumberger, Marcel, 1929, Electrical logs and correlations: The Petroleum Engineer, p. 86.

Schlumberger, Conrad and Marcel, 1929, Communication surle carottage electrique: Deuxieme Congres International de Forages, Paris, Sept., 1929.

Scotty, C. B., and Egan, E. F., 1953, Hole diameter influences neutron-derived porosity: World Oil, v. 136, n. 1, p. 172 et.seq.

Smith, H. D., and Blum, H. A., 1954, Microlaterolog versus microlog for formation factor calculations: Geophysics, v. 19, p. 310–320.

——— Spinner surveys determine formation producing characteristics: Dowell, Inc., The Acidizer, v. 11, n. 10.

Summers, G. C., and Broding, R. A., 1952, Continuous velocity logging: Geophysics, v. 17, p. 598–614.

Swan, L. B., 1947, The electric pilot in permeability surveys: Oil Weekly, v. 125, n. 1, p. 42–46.

Tixier, M. P., 1949, Evaluation of permeability from electric log resistivity gradient: Oil and Gas Journ., v. 48, n. 6.

Weber, G., 1949, Radioisotopes and oil; newest research tool may soon have many routine applications: Oil and Gas Journ., v. 48, n. 31, p. 42.

Wyllie, M. R. J., 1949, A quantitative analysis of the electrochemical component of the S.P. curve: Journ. Petr. Tech., A.I.M.E., T.P. 2511, v. 1, n. 1.

——— 1957, The fundamentals of electric log interpretation, Second Edition: New York, Academic Press, Inc.

GEOPHYSICS, VOL. XXV, NO. 4 (AUGUST, 1960), PP. 748–778, 13 FIGS.

LOG INTERPRETATION IN SANDSTONE RESERVOIRS*

M. R. J. WYLLIE†

ABSTRACT

By comparison with carbonate rocks sandstones are texturally homogeneous; in consequence the interpretation from well logs of the fluid content and physical properties of sandstones is relatively simple. From an exploration standpoint one significant fact must be gleaned from the log: Will the formation of interest produce oil or gas? The precise porosity and thickness of the formation and its exact hydrocarbon saturation are, initially, secondary considerations.

Some of the principal difficulties involved in determining interstitial water resistivity, porosity and formation resistivity are examined. It is confirmed that the so-called "low zone" significantly decreases the resistivity of an oil-bearing sand when this resistivity is found from an induction log. Theory and laboratory experiment confirm that diffusion and convective mixing of the filtrate and interstitial water do little to mitigate the problem. It is suggested that future correction charts for induction logs recognize this fact.

New data bearing on the dirty sand problem show that if formations contain interstitial clay the interpretation procedure suggested by A. J. de Witte is substantially correct. It is pointed out that the real problem is to decide the manner in which the clay content of a typical dirty sand is disposed.

Measurements on the effect of the porosity of sandstones on the difference between velocities through them when dry and fully water-saturated disclose an interesting paradox: The velocity difference is a maximum when the porosity is a minimum. Significant differences in velocity between gas- and water-saturated sandstones are not to be expected in the porosity range of practical significance.

NOMENCLATURE

A = a constant
a = activity; a constant; width of series component in dirty sand model
B = a constant
b = a constant; width of continuous solid component in dirty sand model
c = a constant; width of continuous liquid component in dirty sand model
D_1 = minimum diameter of low zone
D_2 = maximum diameter of transitional segment of low zone
D_3 = maximum diameter of low zone
D_i = material balance diameter of low zone
d = hole diameter; length of liquids fraction of series component in dirty sand model
E_c = electrochemical component of S.P.
E_m = ideal potential of selectively cation-permeable membrane
F = formation resistivity factor; Faraday
f = function of
f_c = fraction of solids that may be considered to be uniformly conductive, e.g., fraction of clays present in a rock
f_J = fraction of current carried by the purely aqueous component of conductivity of a dirty sand

* Presented at the 29th Annual Meeting of the Society, Los Angeles, California. Manuscript received by the Editor August 21, 1959.
† Gulf Research & Development Company, Pittsburgh, Pennsylvania.

G = geometrical factor of induction log
I = resistivity index
K_1 = conductivity of series component of the dirty sand model
K_2 = conductivity of the solid component of the dirty sand model
K_3 = conductivity of the aqueous component of the dirty sand model
k_c = apparent uniform conductivity of electrically conductive solids (conductivity of solution in which solids may be dispersed to give a dispersion with conductivity equal to that of the original solution)
k_o = oil conductivity
k_w = water conductivity
n = saturation exponent; valency of ion (in RT/nF)
R = gas constant
R_a = apparent resistivity
R_i = average resistivity of invaded zone
R_m = mud resistivity
R_{mf} = mud filtrate resistivity
R_o = resistivity of formation 100 percent saturated with water of resistivity R_w
R_s = resistivity of bed adjacent to bed of interest
R_t = true formation resistivity
R_w = interstitial water resistivity
$(R_w)_e$ = apparent water resistivity calculated from S.P. on assumption that water is a solution of sodium chloride only
R_{xo} = resistivity of invaded zone in region fully flushed with filtrate
R_x = resistivity of zone containing unflushed oil and water of resistivity R_w
S_o = oil saturation as a fraction of the pore volume
S_w = water saturation as a fraction of the pore volume
S_{xo} = water saturation in zone of maximum flushing by mud filtrate
T = absolute temperature
t^- = transference number of anion
α = S.P. reduction factor; fraction of the response of proximity log caused by invaded zone; convective mixing coefficient
Δ = maximum thickness of low zone if entirely uniform
ΔD_i = thickness of transitional segment of low zone
$1-\Delta D_i$ = thickness of uniform segment of low zone
ϕ = fractional porosity

INTRODUCTION

Sandstones are generally sufficiently homogeneous in texture to approach closely the criteria upon which classical log interpretion is based. It would be interesting to learn the exact percentage of sandstone formations which yield logs capable of being interpreted with facility; undoubtedly the percentage is high; undoubtedly also it is not 100 percent. A process which involves the vagaries of nature as intimately as does log interpretation makes impossible any

thought of achieving perfection. But percentage successes varying into the high nineties do constitute an attainable objective.

It is the aim of this paper to examine some of the factors which presently militate against the interpretation of logs run through sandstone formations. These factors stem in part from the improper application of known principles and in part from ignorance concerning the physical and chemical phenomena which affect the logging instruments. By trying to separate these two sets of factors it is hoped that benefits both immediate and long-term may accrue.

INTERPRETATION OF IDEAL SANDSTONE RESERVOIRS

It seems redundant to review in detail classical methods of log interpretation. It will suffice to recall that it is necessary to find either explicitly or implicitly three essential parameters. These are:

(1) The resistivity of the interstitial water in the formation of interest, R_w.[1]
(2) The porosity of the formation or, better, the effect the rock structure has on the conduction of electricity through its pores. The latter is defined by a dimensionless parameter known as the formation factor, F.
(3) The true resisitivity of the formation, R_t.

From these parameters is determined:

(4) The resistivity index, I, which is the quotient of R_t and FR_w and which may be related to the interstitial water saturation in the reservoir by an equation of the form

$$I = S_w^{-n}.$$

The exponent n is generally taken to be 2.0 but in sands containing clay is often given a value as low as 1.5. (The significance of this is considered below.)

In the determination of R_w, F (or porosity ϕ), R_t and I numerous assumptions are commonly (and frequently unthinkingly) made. Without these assumptions no interpretation would be possible. This is a hard fact which cannot be gainsaid. Nevertheless certain of the assumptions could be eliminated and the probable accuracy of others better appreciated if the rationale of typical interpretation processes was better understood.

The Determination of R_w

In order to calculate R_w from the S.P. curve it is assumed:

(a) That the S.P. recorded is a maximum value unaffected by geometric effects. In essence this assumes that an open-circuit potential measurement is made.
(b) That the S.P. is entirely electrochemical in orgin, i.e. that no electrokinetic component is recorded.

[1] Throughout this work the standard logging symbols recommended by the AIME are used.

(c) That the chemical species giving rise to the potential consist either of sodium and chloride ions or, in the case of fresh waters, of a mixture of sodium, calcium and magnesium ions with a divalent/monovalent ion ratio uniquely related to total salt concentration. (It is generally assumed also that the mud is a simple solution of sodium chloride. However, this is not a necessary assumption since the effective chemical activity of the mud as sodium chloride can be measured with a suitable ion-exchange membrane electrode. [Wyllie, 1955])

(d) That the potential changes normally measured in the mud column are not upset by gravity segregation of filtrate or anomalous contact between borehole mud and formation water.

This is a formidable array of assumptions. Some are important only under fairly well defined conditions. None, however, is entirely without practical significance.

Assumption (a) is best understood; nevertheless it is not always easy to correct the S.P. for geometric effects even when these are evident. Excellent departure curves have recently been published by Worthington and Meldau (1958) but these require for their proper use an exact knowledge of the resistivity (R_i), and the depth (D_i) of the zone of filtrate invasion adjacent to the well bore, of R_t and of the resistivity of adjacent beds, R_s. Seldom are all known with precision. Experience seems to show that available empirical correction charts in which the correction factor for the S.P. is plotted as a function of R_i/R_m and bed thickness are fully as satisfactory to use. The influence of bed thickness can often be seen by comparing the S.P. of a thin bed with that of adjacent thicker ones. If the thicker beds have a consistent and higher S.P. than the thin bed the higher value can be used for the thin bed also. Clearly this method, although popular, involves yet a further assumption: That the thin bed does not also contain more clay than the thick ones. It remains a great pity that the impossibility of running the selective S.P. log (Doll, 1950) in conjunction with other logs has erected, apparently, an insurmountable economic bar to the commercial exploitation of this ingenious device. Were the static S.P. log generally available to make virtually open-circuit measurements of the S.P., bed thickness and resistivity effects would be negligibly important.

Assumption (b) remains a fertile field for further research. On the one hand Gondouin and Scala (1958) have indicated that only small streaming potential indications are likely unless the electrokinetic properties of a mud filter cake and an adjacent shale differ widely. This view has not been fully shared by the writer and his colleagues (Wyllie, de Witte and Warren, 1958). They have pointed out that the mechanism of streaming potential cancellation supported by Gondouin and Scala does not appear to accord fully with all known facts. They agree that in many wells little if any streaming potential is observed. They also point out that if formation pressures decline rapidly and, possibly, if shales are not bedded,

streaming potentials as large or larger than the electrochemical potentials on which they are superimposed may be generated. It is important from a practical standpoint to realize that, on this theory, large streaming potentials would not normally be expected to arise in wildcat wells; or, to be more precise, wells which penetrate sands that are in pressure equilibrium with adjacent bedded shales. However, it must be pointed out that a complete and fully accepted theory for electrokinetic effects remains to be evolved.[2] It thus behooves the log interpreter to be on guard against treating as purely electrochemical potentials S.P. data which may have a strong electrokinetic component. Where mud control is possible streaming potentials may be minimized under all circumstances by maintaining the mud resistivity at a value below about 0.5 ohmmeter at 70°F.

The electrochemical potential, in terms of the activities of mud and interstitial water, was originally suggested to be (Wyllie, 1949):

$$E_c = 2t^- \frac{RT}{nF} \ln \frac{a_w}{a_{mf}} . \tag{1}$$

Equation (1) assumes that both mud and interstitial water consist entirely of solutions of monovalent sodium and chloride ions. It was pointed out (Wyllie, 1954) that if a solution contained a mixture of monovalent and divalent ions the potential across the shale changed from $RT/F \ln a_w/a_{mf}$ to:

$$\frac{RT}{F} \ln \frac{a_{N_a}' + (a_{c_a}')^{1/2}}{a_{N_a}'' + (a_{c_a}'')^{1/2}} .$$

(This equation is compounded of the potentials produced at each face of the shale. One face is in contact with mud and the other with interstitial water. Both the water and mud contain dissolved salts with activities sodium a_{N_a}' and calcium a_{c_a}' and sodium a_{N_a}'' and calcium a_{c_a}'' respectively.) There is also an additive potential term which represents the junction potential within the shale of the equilibrium ions on the clays in each shale face. It remained for Gondouin, Tixier and Simard (1957) to show experimentally that the shale junction potential was negligible. Thus to a good approximation[3] the chemical potential becomes:

$$E_c = 2t^- \frac{RT}{F} \ln \frac{a_{\text{NaCl}} + a_{\text{Ca+Mg salts}}^{1/2}}{a_m} . \tag{2}$$

[2] The recent work of Hill and Anderson (Trans. AIME, v. 216, p. 203 [1959]), for example, continues to assume explicitly that the properties of shales in situ are identical to those of laboratory samples, and implicitly that the pressure gradient from a borehole into a shale coincides with any salinity gradient. Wyllie, de Witte and Warren (1958) have outlined the experimental observations which confound these assumptions.

[3] In particular the effect of the divalent ions on the junction potential between mud and interstitial water is ignored.

Because the activity of divalent salts enters equation (2) as a square root term it follows that at fractional activities of sodium chloride and divalent ion salts the square root of the latter's activity may greatly exceed the activity of the sodium chloride. Thus the effective activity of a dilute solution containing calcium and magnesium salts may be much greater than its analysis (in terms of mg/L total solids) or its resistivity would indicate. Since the only data normally available to the log interpreter are the S.P. and the mud activity he cannot decide, a priori, whether to use equation (1) or equation (2) to derive the activity of the interstitial water and, from it, the desired R_w. Indeed even if he knows equation (2) is applicable he cannot solve it without further data. Gondouin et al. have, in effect, provided additional data by showing empirically that the ratio of the divalent salt content of a number of typical formation waters to their monovalent salt content is a reasonably good monotonic function of the total salt content, i.e. $a_{Na}/(a_{Ca}+a_{Mg})=f(a_{Na}+a_{Ca}+a_{Mg})$. Hence $(R_w)_e$, an apparent value of R_w, is calculated from equation (1) and corrected on the *assumption* that the formation water is "normal." It is probable that clays in rocks buffer the monovalent-divalent ion ratios of many ground waters at values which depend upon the ionic strength of these waters. But whether that is a truly universal and reliable phenomenon seems to be unknown. Great care should be exercised when interpreting logs if the difference between $(R_w)_e$ and R_w is large. If the R_w derived leads to the interpretation of oil the interpretation should be checked by calculating $(R_w)_e$ for as many adjacent beds as possible. The magnitude of $(R_w)_e$ should vary reasonably smoothly from these to the bed of interest if the positive interpretation is to be considered credible.

The effect of gravity on mud filtrate percolating slowly into highly permeable sand formations is to cause the filtrate to rise and float on the more saline—and thus denser—interstitial water below the first barrier to vertical migration. This phenomenon results in contact logs in which the readings of the deep and shallow investigation curves are either identical or reversed except at the very top of the bed. In itself this phenomenon is no bar to good interpretation. On the contrary the lack of invasion makes the determination of R_t simple (even the contact logs give this quantity), while the existence of gravity segregation immediately reveals homogeneity and high permeability. Porosity may be estimated either from the normal contact log at the top of the sand (or below shale breaks within the sand) or from a density or velocity log. However, these interpretation techniques presuppose that shales and sands are readily distinguishable. Since the resistivities of the two types of bed are frequently almost identical (e.g. in South Louisiana) the S.P. log is the usual distinguishing device.

Evidence was presented by Segesman and Tixier (1959) to show that the segregation of mud filtrate under gravitational forces led also to a serious reduction in S.P. We have observed the same phenomena. Indeed, as shown in Figure 1, we have examples in which the S.P. opposite a considerable section of permeable bed has entirely disappeared in the course of 19 days. In the example shown a

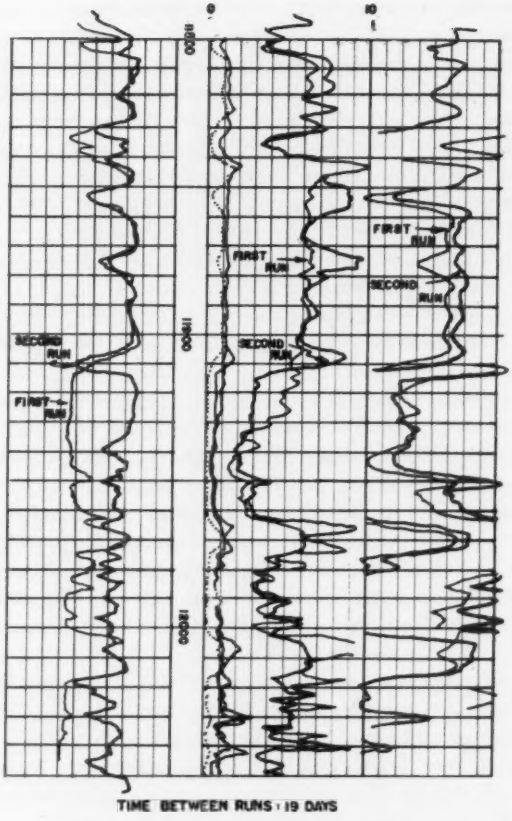


FIG. 1. Effect of gravity segregation of mud filtrate on S.P.

spurious baseline normally indicative of shale now characterizes some 20 ft of highly permeable sand. The change in the short normal resistivity in the same time shows that gravity segregation is almost certainly its proximate cause. Apparently (although it seems incredible) the amount of filtrate which penetrates the mud cake over the interval 11,915–11,935 ft is negligible. Thus the interstitial water and mud over this interval are separated only by the filter cake which is itself under a differential pressure of some 3,000 psi. Under such a pressure the cake behaves as a shale[4] and the S.P. is reduced to zero. This is schematically

[4] The surprising electrochemical efficiency of a compacted filter cake in retarding anion movement also leads to such cakes having salt filtering characteristics. [See Wyllie (1955) and McKelvey, Spiegler and Wyllie (1959).] There have been reports that aqueous liquid collected by formation

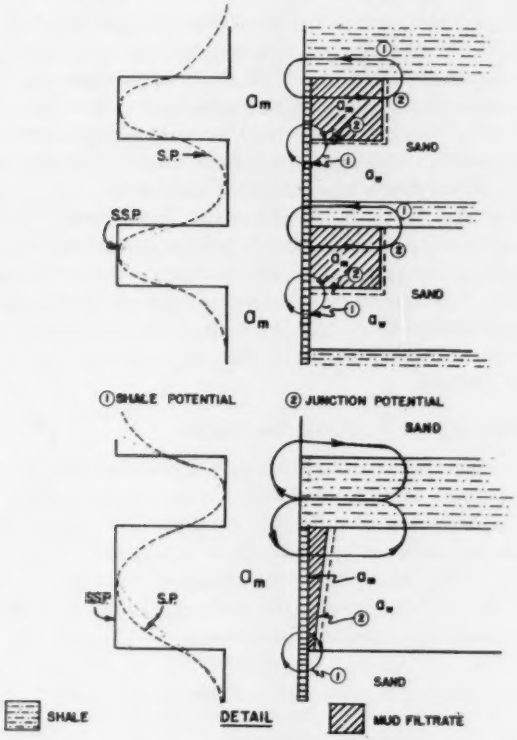


FIG. 2. Effect of distribution of filtrate on S.P. when mud cake exhibits the electrical properties of a shale.

shown in Figure 2; both the static S.P. and the expected actual S.P. are indicated.

The important practical consequence of gravitational segregation of filtrate and its attendant electrical effects is amply shown in Figure 1. It is clear from Figure 1 that if serious errors in interpretation are not to be made in highly permeable sands logging should not be unduly delayed after drilling has taken place. The economics of such a decision will be more favorably met if the ingenious device recently developed by the Sun Oil Company (Chaney et al., 1959) for logging while drilling is used to produce S.P. curves before the filtrate invasion can become excessive.

The comparison of the drill-stem S.P. records with later, routine logs should prove peculiarly illuminating. In particular, it may cast light on the permeability

testers is sometimes less saline than either the mud filtrate or formation water. Laboratory experiments have confirmed the desalting ability of filter-cakes; it seems possible that in situ this property of filter cakes is enhanced.

paradox implicit in the above discussion. The direct inference from the S.P. data of Figure 1, as shown in Figure 2, is that actually no filtrate is percolating through the filter cake from 11,915–11,935 ft although a pressure differential of 3,000 psi is operative. It is important to realize that even a thin film of filtrate passing through and rising behind the mud filter cake would destroy almost entirely the potential which leads to the apparent "shale" baseline in the interval 11,915–11,935 ft. This is shown in a detail in Figure 2.

The so-called "saw tooth S.P." (Segesman and Tixier, 1959) is another phenomenon which has its origin in gravity segregation of mud filtrate. From an interpretation standpoint it presents few problems. However, we differ from Segesman and Tixier in one particular. Our calculations show that the best approximation to the static S.P. is the S.P. which characterizes the saw tooth crests (i.e. the maximum S.P. recorded); it is not the apparent S.P. plateau recommended by these authors.

The Determination of Porosity/Formation Factor

Producing sandstones are, with singularly few exceptions, characterized by porosities of 10 percent or more. The neutron log, because of the nature of its empirical porosity-deflection relationship, is inherently most reliable only when the porosities it is reflecting tend to zero. Thus we may omit the neutron log from consideration as a significant porosity measuring tool in the evaluation of sandstone reservoirs. With this omission the best logs available from which either formation factor or porosity may be derived are:

Electrical:	Microlog
	Microlaterolog
	Proximity log
Nuclear:	Density log
Acoustic:	Continuous velocity log

As is now well known the Microlog or similar contact device gives surprisingly reliable values of R_{xo} when (a) mud cakes are less than about $\frac{1}{4}$ inch thick and (b) values of R_{xo}/R_{mf} are less than about 30. The latter requirement implies porosities in excess of about 15–20 percent. The Microlog is at its best when R_{xo}/R_{mf} is less than 20 and mud cake thickness less than $\frac{1}{8}$ inch.

The Microlaterolog and Proximity log are basically similar devices. Both are focussed, both aim to measure R_{xo} and both require for reliable results a radial depth of filtrate invasion which considerably exceeds that needed by a Microlog. This requirement for a Proximity log is well exemplified by Figure 3. In order for the apparent Proximity log reading to be 80 percent dependent upon the resistivities of the invaded zone the value of D_i must be at least 24 inch, i.e. radial invasion depth must be about 8 inch. The chief advantage of the Proximity log over the Microlaterolog is that the rather stringent requirement of the latter concerning maximum mud cake thickness ($\frac{1}{4}$ inch) does not apply to the Proximity log. The need for a significant depth of filtrate invasion is a real drawback to

the use of the focussed devices in certain practical instances of importance. For example, the value of R_{xo} or R_i is urgently needed for the interpretation of dirty sands. Yet in many such sands the swelling of the clays in contact with the entering mud filtrate appears to inhibit further invasion. In such cases a focussed device tends to reflect R_t, not R_{xo}.

Provided the borehole wall is reasonably smooth the gamma-gamma density log is an excellent tool with which to derive density and, hence, porosity in those cases where the broad lithology of the formations penetrated is known. Yet the density log is not being widely used. It is uncertain whether this comparative neglect stems from lack of sufficient instruments in the field, the necessarily slower speed of running the log compared to that customary in making electric or velocity logs or to the mildy complex procedure for converting log readings to

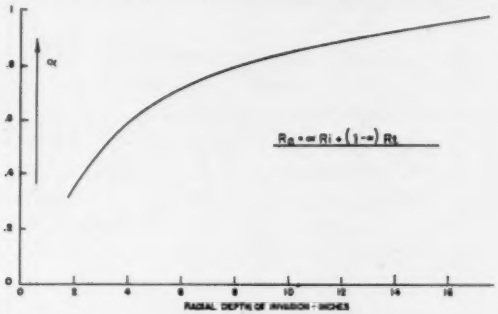


FIG. 3. Effect of invasion depth on the response of a proximity log.

densities. In regard to the last, if diminution in source strength with time were compensated instrumentally by the operator, there seems no reason in principle why any but the most highly collimated logs should not be arranged to record densities directly. In the case of a high degree of collimation some correction for the presence of the mud cake seems inevitable.

The density log even in its present form is simple to use. Provided a reasonable figure for the density of the solid matrix material is assumed the porosities obtained should be good to ± 2 porosity percent in the porosity range 15–30 percent. At low values of porosity (approximately <5 percent) the accuracy of the calculation is dominated by the accuracy of the assumed solid density. However, this should not prove a bar to the use of the density log in practical cases involving potentially productive sandstones.

In the interpretation of velocity data in terms of porosity it has been found best to use the time-average equation (Wyllie, Gregory and L. W. Gardner, 1956, and Wyllie, Gregory and G. H. F. Gardner, 1958). For sandstones this equation has given satisfactory results when a matrix velocity of about 19,500 ft/sec is used, provided (and this is sometimes ignored) the conditions for the

application of the simple time-average equation are met. In particular all laboratory experiments show that the only velocity to which the time-average equation is applicable is the so-called terminal velocity. This is the velocity recorded at high differential pressures, i.e. when the difference between the pressure applied to the rock frame and pore fluids is large. The absolute pressures applied to each are only of second-order importance. A typical record of the relationship between velocity and applied pressure for the same rock dry and water-saturated is shown in Figure 4. This figure indicates that a pressure differential of some 7,000 psi is required before either velocity approaches a terminal value. It is now evident from a comparison of appropriate laboratory and field data that the pressure-velocity relationship typified by Figure 4 is only qualitatively valid in the

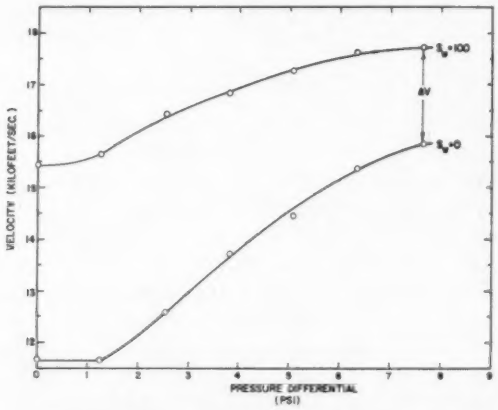


FIG. 4. Effect of pressure on the velocity through a dry and water-saturated sandstone specimen.

field. In situ a rock requires a far smaller differential pressure to reach a terminal velocity than does a fragment of it in a laboratory test. This indicates to the writer that the mere act of cutting a core alters profoundly (and probably irreversibly) the micro-structure of the rock. Nevertheless the differential pressures required for rocks to attain terminal velocities in situ may be (or may have been in the case of older cemented rocks) several hundreds or even thousands of psi. It is clearly necessary to assume a terminal velocity before the time-average equation can be used to estimate porosity. It is a decided weakness of present techniques that no rigid criterion is available to judge whether the rock is, or has been sufficiently stressed or cemented to justify the equation's use. It has been proposed by Tixier, Alger and Doh (1958) that the velocity of shales adjacent to sands be used to remedy this deficiency. If the shale velocity exceeds 10,000 ft/sec the equation is applicable; if the shale velocity is less than 10,000 ft/sec a simple empirical method of correcting the sand velocity in terms of the ratio of the adjacent shale velocity to 10,000 ft/sec is suggested. The method also

involves the use of an arbitrary "coefficient of shale compaction." This coefficient may be genuinely necessary or it may reflect, in part at least, the variations in the velocity of shales adjacent to boreholes which have been discussed by Hicks (1958). These may be as much as 25 percent. In any event the suggested process seems to be undesirably empirical. Since laboratory data on pressure vs velocity do not seem to be quantitatively relevant, it appears that further field studies of detailed porosity-velocity correlations under differing stress conditions are necessary.

Tixier et al. (1958) also suggest that when using the time-average equation to calculate the porosity of oil- or gas-bearing zones the apparent porosity so found should be reduced by 10–20 percent if the sand is oil-bearing and by about 30 percent if gas-bearing. These corrections seem based on the form of the time-average equation and the fact that the velocity of oil or gas is less than that of water.

It is quite possible that present logging devices sometimes record apparent velocities which are lower in oil- or gas-saturated zones than in otherwise similar water-saturated zones. The reason for these differences is more likely to reside in the acoustic peculiarities of the three types of rock (particularly their relative ability to attenuate logging signals) than in genuine velocity differences.

Laboratory experiments show that, paradoxically, the difference in the terminal velocities of water-saturated and dry sandstones *increases* as porosity *decreases*, i.e. increases as the amount of cementing material in the pores increases. This is shown in Figure 5. It is apparent that the velocity difference in the practically important porosity range from 15–35 percent is less than 2 percent; only for porosities less than 10 percent does the velocity difference exceed 5 percent. Since these figures relate the dry and water-saturated rocks the differences are maximal. For rocks containing irreducible water and gas or oil the differences are less. In other words in compacted sandstones genuine velocity differences caused by the presence of hydrocarbons are negligible in the porosity range of commercial interest. Observed velocity differences must, therefore, stem from other causes; probably attenuation is of major importance, but dispersion is also possible. Work on the effect of porosity, compaction and saturation on the attenuation of acoustic energy in sedimentary rocks is presently being conducted by the writer and his colleagues. It will suffice to say here of these studies that they indicate the importance of attenuation measurement as a factor in the location of oil- and gas-saturated rocks.

Laboratory data, therefore, do not support the contention that factors are required to correct the velocities of sandstones which contain oil or gas to an equivalent 100 percent water velocity before the time-average equation can be used. In simplest terms the correction factors advocated are so large that they would lead to velocities for oil- or gas-saturated rocks lower than the velocities of the same rocks dry; this is implausible. This is not to say that the factors of Tixier et al. are necessarily erroneous. Merely that they are empirical correction factors. They probably allow for the fact that in sands saturated with more than

one fluid phase signal attenuation prevents the measurement of the same first arrivals of energy as are recorded in the laboratory. The reduced velocities recorded thus make difficult the accurate calculation of porosities in even well compacted sandstones if these are petroliferous. Nevertheless this is a small price to pay for the *diagnostic* value of the reductions. Logs are interpreted to locate oil-saturated rocks; the precise porosity of these rocks is initially of secondary importance. If, as a matter of practical fact, the presence of oil or gas leads to apparently low velocities and if these low velocities are associated with higher than normal resistivities, interpretation is rendered easier and more certain. There is a

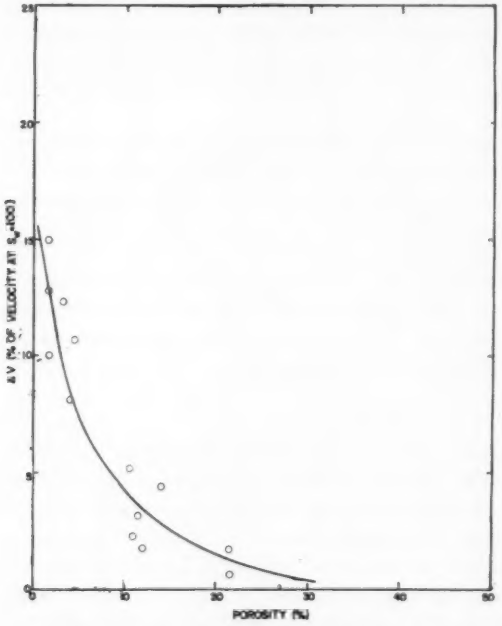


FIG. 5. Effect of porosity on the difference in velocity through dry and water-saturated sandstones.

prevalent fetish that log interpretation is only "good" if it produces results in terms of X percent porosity and Y percent water saturation. These are the terms of the reserves engineer. Log interpretation in the exploration phase is good if it leads to no oil or gas sands being missed, bad if it does. When the extent, permeability and producing mechanism of a reservoir are all unknown, it is academic to strive for the precise calculation of porosity and saturation.[5]

[5] In the interest of brevity the relationship between porosity and formation factor has not been considered in the above. It is a subject to which too little attention has been directed. Recently a derivation has been given (Wyllie and Gardner, 1958) which indicates that the limiting formation

The Determination of R_t

The trend in logging is now wholly toward the use of focussed devices to measure true resistivity. While the classical normal and lateral curves are still frequently run their importance is declining. Their limitations are well known and methods to overcome these limitations by the use of more complex departure curves seem futile.

The determination of R_t in sandstones is now considered the prerogative of the induction log; the most popular present form of the device is the so-called 5FF40 inch. This is a five-coil focussed system with a spacing of 40 inch between the main coils. It is generally run with a 16 inch normal log and a S.P. log, the 16 inch normal reading being used to correct the induction log resistivities for the effects of the zone of mud filtrate invasion near the well bore. The technique of calculating R_t from the apparent resistivities read by the normal and induction logs will not be elaborated. It appears to be reliable and satisfactory in the case of invaded water sands or negligibly invaded oil sands. In the case of more deeply invaded oil sands the effect of the so-called "low zone" on correction procedures (Campbell and Martin, 1955) is still controversial (de Witte, 1957). The low zone arises because of the existence of a phenomenon which, though long known in water flooding, was only belatedly recognized as a factor in log interpretation. When mud filtrate invades a sandstone which contains oil and water both the oil and the water are displaced and pushed radially outward from the well bore. However, the oil is pushed more rapidly than the water with the result that, after a short time, the saltus in the oil saturation does not coincide with the transition between the filtrate and water. If the oil content of an invaded formation is high there is a transition between the oil not displaced (the residual oil) and the virgin oil saturation. If the oil saturation is initially low the displaced oil may form a bank and the oil saturation in a radial direction outward from the borehole will be residual—banked—virgin. In most cases of exploratory interest no bank is formed and there is only a transition from a uniform residual oil saturation[6] to a uniform virgin oil saturation. The sharpness of the transition or front depends on the rate of infiltration, the wettability characteristics of the rock and its capillary and relative permeability characteristics. Experiments we have car-

factor in homogeneous rocks is $F=1/\phi^2$; reasons for the existence of lower formation factors at a particular porosity are quantitatively obscure. While other empirical formulations based on inadequate experimental data exist, a simple relationship which has an accuracy adequate for the qualitative interpretation of sandstones if $F=0.75/\phi^2$.

[6] This is strictly true only if, in water flooding terminology, there is no oil production after water breakthrough. When the viscosity of the oil in the invaded formation is high, it is common for the oil saturation behind the saltus to decrease slowly, i.e. there is a small flow of oil accompanying the flowing water. In such a case the resistivities R_{xo} and R_s in Figure 6 increase slowly in a radial direction, R_{xo} from a minimum behind the mud cake to a maximum at the diameter D_1, and R_s from a minimum at diameter D_2 to a maximum at D_3. Such a variation in saturation and resistivity in the radial direction in most cases does not alter significantly conclusions based on the model shown in Figure 6.

ried out in water-wet Berea sandstone (porosity 20 percent, permeability 300 md) at typical infiltration rates reveal that the transitional zone may be less than one inch thick. Excellent agreement with predictions based on Buckley-Leverett theory was observed. It is conceivable, however, that for other rocks the zone may be much thicker although, in typical cases, this is not very likely.

If it is assumed that the transition zone is thin enough to be treated as a discontinuity in saturation with saltus $S_{xo}-S_w$ the effect of the zone lying between the virgin formation and the rock which contains only residual oil and filtrate can be sought. It is the segment of this zone encompassing the transition from water to filtrate in the presence of residual undisplaced oil together with the adjacent segment containing residual oil and water only which gives rise to the low zone. This is shown in Figure 6. The two segments form as filtrate displaces the interstitial water with which it is miscible. At typical infiltration rates the mixing is entirely due to convective fluid motion, i.e. mixing by diffusion is negligible. These

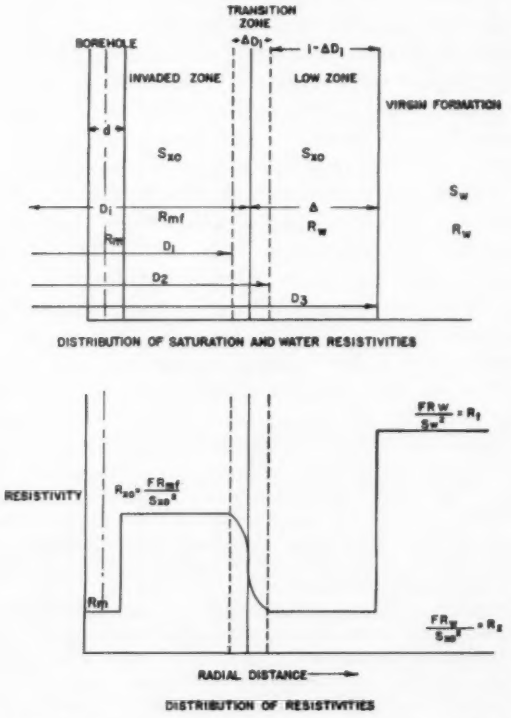


FIG. 6. Distribution of resistivity and terminology used to describe an oil sand invaded by mud filtrate.

factors are discussed in detail by Raimondi, Gardner and Petrick (1959). They show that a parameter α, principally dependent upon absolute pore size and pore-size distribution, can be used to characterize the convective mixing characteristics of a rock. The mixing coefficient α has not been accurately measured when stationary oil is present in a rock but rough experiments suggest that α is diminished by the presence of oil, i.e. that the width of a mixing zone between two miscible fluids in a rock is reduced somewhat by the presence of residual oil in the rock pores.

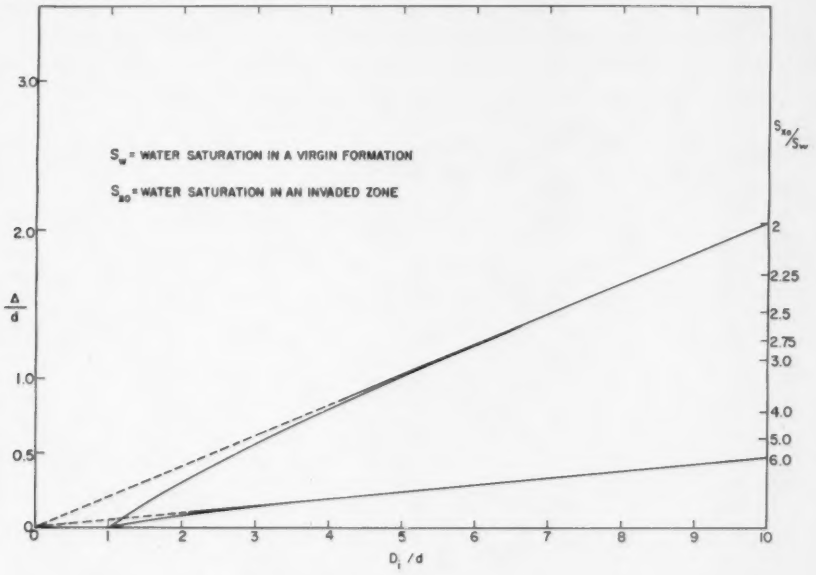


FIG. 7. Relationship between depth of filtrate invasion and width of low zone.

The maximum thickness of a low zone (Δ in Figure 6) has been calculated by A. J. de Witte (1957) on the assumption that both the oil-water front and the filtrate-water front are vertical. On this assumption he was able to show that the effect of the low zone on standard procedures for connecting R_a recorded by present induction logs with R_t was considerable, particularly when invasion was deep. The effect of a mixing zone on reducing the abrupt transition from filtrate to water was not considered. Figure 7 expresses Δ/d as a function of D_i/d for values of the parameter S_{xo}/S_w and corrects some inaccuracies in de Witte's similar graph. The thickness of the low zone rapidly becomes directly proportional to the depth of invasion. If the effect of the filtrate-water transitional zone is now considered the resultant apparent resistivity R_a is given by:

$$\frac{1}{R_a} = \frac{G_{xo}}{R_{xo}} + \int_{D_1}^{D_2} \frac{dG}{R} + \frac{G_z}{R_z} + \frac{G_t}{R_t},$$

where G is the geometrical factor and R_z is the resistivity of the uniform section of the low zone. The function G is determined by the diameter D and the type of logging instrument (Schlumberger, 1958).

When a fluid miscibly displaces another fluid of the same viscosity in a porous medium, the curve of concentration of one component vs distance at the interface of the two fluids is S-shaped. We may assume without serious error for salt solutions that their conductivity at any temperature is a linear function of their salt concentration. Thus conductivity varies in a similar S-shaped manner across the transitional zone. This S-shaped curve may be approximated by a straight line as shown in Figure 8; then $1/R$ varies linearly with D.

If this is so it follows from Figure 9, on which a typical G-D curve for an induction logging device is plotted, that:

$$\frac{1}{R} = \frac{1}{D_2 - D_1}\left[\frac{D - D_1}{R_z} + \frac{D_2 - D}{R_{xo}}\right] = a + bD.$$

That is when $D = D_1$, $R = R_{xo}$ and when $D = D_2$, $R = R_z$.

Then:

$$\int_{D_1}^{D_2} dG/R = \int_{D_1}^{D_2} (a + bD)dG/dD \cdot dD$$

$$= [(a + bD)G]_{D_1}^{D_2} - b\int_{D_1}^{D_2} G \cdot dD$$

$$= \frac{G_z}{R_z} - \frac{G_{xo}}{R_{xo}} - b(D_2 - D_1)\overline{G},$$

where $\overline{G}$ is the mean value of G between D_1 and D_2. Thus:

$$1/R_a = \frac{G_1 - 0}{R_1} + \frac{G_z}{R_z} - \frac{G_{xo}}{R_{xo}} - \left(\frac{1}{R_z} - \frac{1}{R_{xo}}\right)\overline{G}$$

$$+ \left(\frac{G_3 - G_2}{R_z}\right) + \left(\frac{1 - G_3}{R_t}\right) = \frac{\overline{G}}{R_{xo}} + \frac{G_3 - \overline{G}}{R_z} + \frac{1 - G_3}{R_t}.$$

From this derivation it follows that the transition zone between R_{xo} and R_z may be replaced by a sharp boundary, the diameter of this boundary being the point where G is equal to the mean value between G_1 and G_2. Although somewhat dependent upon the magnitude of D_1 and D_2, the fact that the relationship between G and D is straight in practical cases makes it clear that D_i is a good approximation to this point. Thus de Witte's limiting calculations for the effect on the induction log of the low zone when deriving R_t for petroliferous beds are essentially

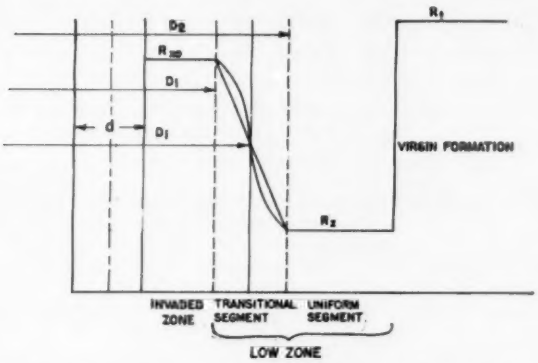


FIG. 8. Distribution of resistivities in the vicinity of the borehole of an invaded oil-bearing formation.

correct, i.e. the effect of mixing at the filtrate-water transition does almost nothing to ameliorate the difficulty. It would, therefore, seem a highly desirable matter to prepare departure curves for induction logs which specifically take cognizance of and correct for the presence of a low zone. This is easier said than done particularly if it is to be achieved succinctly. Whether the new 6FF40 inch induction log, which is focussed more deeply than the 5FF40 inch, will be relatively more immune to the low zone is not yet clear.

It is of interest in this connection to point out some additional properties of the transitional segment and the low zone proper. Using the Raimondi-Gardner-Petrick theory of the development of a mixing zone in miscible displacement it can be shown that the width of the transitional segment of the low zone increases directly with $D^{1/2}$ whereas the uniform segment has a length which increases directly with D. Thus the transitional segment of the low zone grows less rapidly

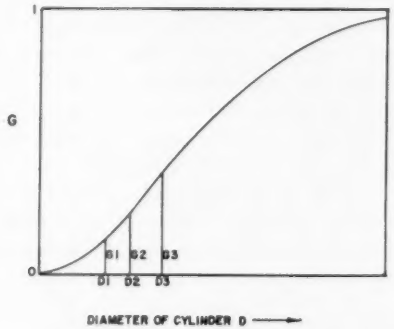


FIG. 9. The G factor as a function of the diameter of cylinders concentric with the borehole (5FF40" induction log).

than does the uniform segment. Relevant data are tabulated below for the case of an 8-inch diameter hole; the original water saturation assumed in the virgin zone is 25 percent and the residual oil saturation 25 percent also. The mixing coefficient α is given the typical figure of 0.2 inches. D_i is the diameter of the center of the transitional segment of the low zone; its thickness is ΔD_i; $1-\Delta D_i$ is the thickness of the uniform segment of the low zone.

DEVELOPMENT OF TRANSITIONAL AND UNIFORM SEGMENTS OF MIXING ZONE WITH INVASION DEPTH

Mean Invasion Diameter D_i inches	Uniform Segment $1-\Delta D_i$ inches	Transitional Segment ΔD_i inches
16	1.7	2.3
32	4.0	3.7
56	7.0	4.9

The relative sizes of the transitional and uniform segments of the low zone as a function of invasion depth are readily seen.

The above analysis thus confirms de Witte's conclusions that in petroliferous beds the 5FF40 inch induction log will tend to read a much lower value of R_a than current departure curves implicitly recognize. If D_i/d exceeds two the value of R_a may easily be less than 50 percent of that expected in the absence of a low zone. It is difficult to generalize because both the ratio R_{mf}/R_w and the quantity of residual oil undisplaced by filtrate influence the magnitude of the effect.

Nevertheless it would be fair to claim that an unrecognized low zone may reduce by a factor of two or more the resistivity index ultimately calculated. Except in those cases where the calculated resistivity index is about 3–4 a reduction factor of two will not be quantitatively significant (i.e. will not lead to a productive sand's being left untested). As we have already noted it is egregiously unnecessary to calculate a precise water saturation for a formation in a wildcat well. Thus the low zone error should not affect the correct diagnosis of a highly oil-saturated sand. In cases where the true water saturation of a bed is about 30–35 percent a reduction of the apparent resistivity by a factor of two would reduce I from 10 to 5, i.e. to a value normally indicative of uncertain production. In a wildcat operation, when in doubt, the rule should be to test. It is, however, possible that genuinely high water saturations in oil-productive sands mainly tend to exist in formations which are somewhat dirty and which are not deeply invaded. Thus there may be a natural compensation for some of the possible adverse effects of the low zone. Nonetheless the phenomenon should now be recognized as a necessary factor in the compilation of correction charts for induction logs.

The Determination of Resistivity Index

The resistivity index is determined when R_wF and R_t are found. In practice the resistivity index is of little value unless it can be related to saturation. It is

the relationship between I and S_w we wish to consider here. This relationship is usually assumed to be $I = S_w^{-2}$ when sands are clean. When sands are dirty it is now widely recognized that the $I - S_w$ relationship is more complex. In particular it is known that even for a highly productive dirty sand the value of I may be quite small. How to evaluate the significance of a calculated value of I is the exigent problem.

Let us consider briefly this problem as it applies to clean sandstones. In such sands, if isotropic and preferentially water-wet, the resistivity index often seems to be equal to the inverse square of the fractional water saturation. This agrees with simple theoretical expectations. It must be emphasized that in laboratory experiments departures from an exponent n of two in the relationship $I = S_w^{-n}$ are to be expected if tests are made on specimens which are not perfectly homogeneous. Since perfect homogeneity is entirely incompatible with nature small variations from a figure of two are not disturbing. (It is probably because of a greater tendency to homogeneity than any other single factor that unconsolidated sands follow so closely the inverse square relationship.) As will be shown below, if sands contain clay, the value of the exponent may appear to be smaller than two. What is rather disturbing, because there is no explanation for it, is the apparent fact that synthetic clean and homogeneous water-wet porous media (alundum, Pyrex glass) may have exponents as high as 2.5 (Wyllie and Gardner, 1958). In itself this is not important; in its implication that we are grossly ignorant of the factors which influence the magnitude of the exponent, it is.

Rust (1952) also gives laboratory data which indicate that sandstones may have exponents as high as 2.4. A study of his data reveals that these exponents are not constant. Initially they are about 2.0 but they increase slowly as wetting phase saturation decreases. Since the non-wetting phase used to displace the water in Rust's experiments was iso-octane, the high resistivity indices may really reflect the fact that some change of wettability was accompanying the change in water saturation. In our experience only if the iso-octane used was scrupulously cleaned of minute traces of aromatic contaminants could 100 percent wettability of the core surfaces by the water used be assumed. This precaution is not mentioned in Rust's paper. If a change of surface wettability does indeed serve to increase the apparent value of the resistivity index exponent, further complications of practical import can be envisaged.

Thus the validity of assuming an exponent of 2.0 in the interpretation of clean sands must surely be weighed against current theories of the existence of "Dalmatian Wettability" in situ, i.e. the view that minute areas of some rock surfaces are oil-wet while other areas are water-wet. The writer has never seen an electric log which would indicate that a formation was either completely wetted by oil or, indeed, was even substantially oil-wet. This is not to say that such formations cannot or do not exist. However, it is evident that the vast majority of oil-producing formations are substantially water-wet. But substantially is a qualitative term. The only reasonable conclusion presently possible is that

Dalmatian wettability may be real (with the spots being preferentially oil-wet) and that, if it exists, it probably increases the resistivity index at a particular relative level of oil and water saturations. The effect would be beneficial because it would serve to sharpen the resistivity contrast between oil- and water-bearing formations. Again the futility of early quantitative interpretation is stressed.

Of greater importance by far than the fact that high resistivity index exponents may be observed in clean uniform sands is the problem of the apparently small exponents which characterize sands containing clay minerals. It is perhaps desirable to amplify what is meant by "apparently." The exponent n is genuinely small if the ratio $I = R_t/R_o$ is related to saturation by an equation of the form $I = S_w^{-n}$. Whether the use of a small value for the exponent (which, in any event, is no longer saturation-independent) is of any value practically is controversial. It is the burden of this discussion that its use is definitely unprofitable.

Some four or five years ago the problem of interpreting dirty sands was actively investigated by a number of oil and service companies (Perkins, Brannon and Winsauer, 1954; Poupon, Loy and Tixier, 1954; Wyllie and Southwick, 1954). In spite of the use of different approaches to the problem one common conclusion was reached. If a dirty sand contained no oil or gas its resistivity index would be about one if this index were calculated conventionally from *electric log* measurements. If the index exceeded one the sand might be petroliferous. It was agreed that pipeline oil might be produced from a dirty sand for which the calculated resistivity index was only two or three but no quantitative method of relating this resistivity index to oil saturation or oil producibility was agreed upon. Basically two factors caused this disagreement. First, no experiments had been performed using oil-containing dirty sands. Secondly, no theory had been expounded to account for the effect of oil in a dirty sand on both S.P. and resistivity. However, the paper by Poupon, Loy and Tixier (1954) did propose a scheme for the quantitative interpretation of dirty sands. This scheme was based on prior theoretical developments by Doll (1950) and undoubtedly was correct when applied under the conditions assumed by Doll, i.e. to sands composed of interlaminated clean sands and shales. It was extended, mainly by default, to dirty sands in which the clay was disposed interstitially and the technique is now widely used. The only important alternative scheme for interpreting sands with an interstitial clay content is that proposed by de Witte (1957). It is believed de Witte's method has not been widely used. This is partly because the method has been unpublicized but principally because its derivation is ingenious but intuitive. In the following it will be shown that de Witte's scheme of interpretation seems very nearly correct when applied to practical cases. It is then an inevitable conclusion that the Schlumberger scheme of interpretation is correct only when applied to interlaminated clean sands and shales; it is incorrect when applied to sands containing clay interstitially. From a practical standpoint the issue is, however, much less clear cut. This will be discussed in greater detail below.

Wyllie and Southwick (1954) proposed a three-component model for a sand containing interstitial clay. They pointed out that such a model served to explain the relationship observed when $1/R_o$ was plotted against $1/R_w$, i.e. that this plot, although almost a straight line at high values of $1/R_w$, curved markedly as $1/R_w \rightarrow 0$. The concepts of the model were subsequently expanded (Sauer, Southwick, Spiegler and Wyllie, 1955) and then applied successfully to the problem of calculating potentials across porous materials containing particles of ion-exchange materials (McKelvey, Southwick, Spiegler and Wyllie, 1955; Spiegler, Yoest and Wyllie, 1956). However, it has been the extension of the model's use to the complex problem of calculating the thermal conductivities of rocks and

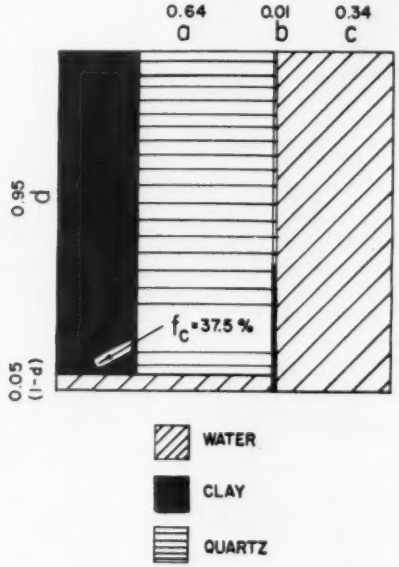


FIG. 10. Model of an unconsolidated sand (porosity 40%, clay content 37.5%, water saturation 100%).

porous materials which has been carried out both by Kimura (1957) and by the writer and his associates that has, paradoxically perhaps, led to light being cast on the interpretation of dirty sands. The calculation of the thermal conductivity of a rock composed of particles of more than one mineral and saturated with various fluids is a problem essentially equivalent to calculating its electrical conductivity. It is a more difficult problem because none of the solid or fluid components is a thermal insulator. In the electrical problem only the brine and the clay minerals are conductors; quartz or calcite grains and oil are effectively non-conductors.

Figure 10 shows to scale the model as applied to an unconsolidated sand whose

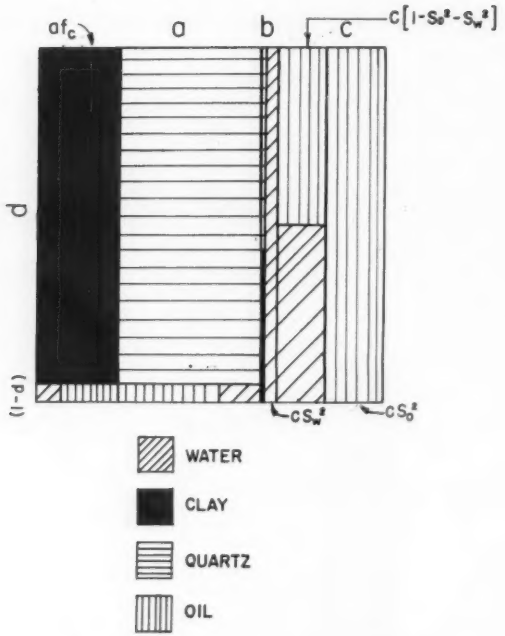


FIG. 11. Model of an unconsolidated sand (porosity 40%, clay content 37.5%, water saturation 30%, oil saturation 70%).

solid particles are composed of 62.5 percent non-conductive quartz and 37.5 percent conductive clay. In Figure 11 the same sand contains within its pores oil and water; the oil saturation, S_o, is 70 percent and the water saturation, S_w, 30 percent. The model is a square of unit side and conduction takes place from edge to edge through three components which are in parallel but insulated from one another. These components are:

(1). A component of length a perpendicular to the direction of current flow. It consists of two portions in series, one portion comprised of solids and the other of liquids. The solids portion has length d and the liquids $(1-d)$. (This component represents conduction in series through grains and pore liquids. It is zero in a clean sand because all the solids are non-conducting.) When two phases are present in the solid portion the area ad is divided as shown in Figure 10 in accordance with the fractions of each phase present.

(2). A component of length b perpendicular to the direction of current flow and unit length in the direction of flow. (This component represents conduction through the solid particles themselves. Thermally it is the rock

conductivity in vacuo. The parameter b may be viewed as the reciprocal of the formation factor of the rock solids.) When two solid phases are present b may be divided according to the percentage of each as shown in Figure 10. This simple division is permissible when b is small. When b is large (consolidated rocks) the more elaborate procedure shown in Figure 12 is used.

(3). A component of length c perpendicular to the direction of current flow and unit length in the direction of flow. (This component represents conduction through the liquid in the pores of the rock. The parameter c in a clean rock equals k_o/k_w, i.e. $c=1/F$.)

Relationships which help to define the parameters, a, b, c and d are the following:

$$a + b + c = 1$$
$$ad + b = (1 - \phi)$$
$$c = 1/F.$$

If it is assumed that a $F-\phi$ relationship has been established, only b remains to be found for the model to be fully delineated. Work carried out on the thermal properties of rocks has led to progress being made in the correlation of b and $(1-\phi)$. This is, in its essentials, a problem entirely analogous to establishing a $c-\phi$ (i.e. $F-\phi$) relationship. This work has also led to experimental verification

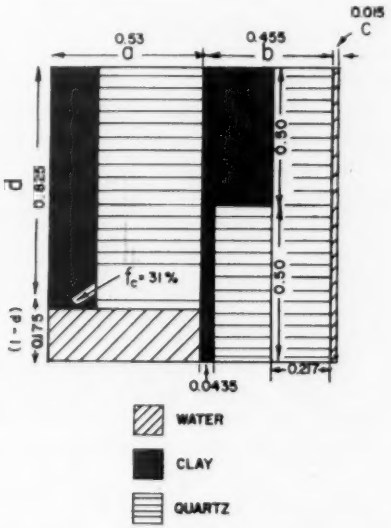


FIG. 12. Model of a consolidated dirty sandstone (porosity 10.8%, clay content 31%, water saturation 100%).

of the correct method of incorporating in the model the effects of fluids in the pores of a rock on thermal and electrical conductivity. Clearly the presence of the fluids does not alter the basic rock structure; hence the model shown in Figure 10 remains unchanged. Clearly also the total pore area of the model, $a(1-d)+c=\phi$, must be divided in the proportions S_o and S_w. Also the conductivity of a clean sand at a saturation S_w must be cS_w^2 (for the exponent $n=2.0$). The method of reconciling these requirements is shown in Figure 11.

The interpretation of Figure 11 is the following. When two phases (oil and water) are present in a rock conduction in the pores can be separated into four mechanisms. The first is conduction only through the water phase—in magnitude this is $cS_w^2k_w$. The second is conduction only through the oil phase—in magnitude $cS_o^2k_o$ (electrically this is zero since the oil conductivity k_o is zero.) The third is conduction through oil and water in series—in magnitude

$$c[1 - S_0^2 - S_w^2]\left[\frac{k_0k_w}{0.5(k_0 + k_w)}\right],$$

(electrically this is also zero since $k_o=0$). A fourth is conduction through the water in the pores and through the clay particles, the two being in series. The presence of oil diminishes this component. In magnitude this conductivity is

$$\left\{\frac{1}{f_c a S_w}\left[\frac{d}{k_c} + \frac{(1 - d)}{k_w}\right]\right\}^{-1},$$

where f_c is the fraction of solid matrix which has conductivity k_c.

It is a noteworthy geometric fact that no matter what the saturations S_o and S_w may be, when the remaining volume $c[1-S_o^2-S_w^2]$ is divided in half transversely the fractions of the area c occupied by oil and water are in the ratio S_o to S_w. This ratio is required from the material balance view of the model. The construction is shown in Figure 11.

For simplicity and in order to show a reasonable value of c, Figures 10 and 11 refer to a dirty unconsolidated sand. The same model is shown applied to a dirty consolidated sand in Figure 12. The properties of this sand correspond closely to Sample 13 of Suite n. 2 in the paper of Hill and Milburn (1956). In particular the volume of solid grains which is comprised of clay minerals is 31 percent.[7] Note that $c=1/F$ is now very small (0.015) since $F=67$. On the other hand b is 0.455 and is almost as large as a. It is necessary to divide b as shown. The division is accomplished in a manner analogous to that used to segregate the fluids in the pores in Figure 11. The division reflects the fact that conduction through the solid phases may be through either clay or quartz separately or through both in

[7] This percentage may seem high. However, since the porosity is 10.8 percent and the measured cation-exchange capacity is 0.7 milliequivalents per cc pore volume, it is easy to calculate that the exchange capacity of the 31 percent clay present is 10.4 milliequivalents per 100 gram. This is a very reasonable figure.

series. Electrically only conduction through the clay is physically possible. The limiting resistivity of this rock is about 160 ohmmeters when saturated with distilled water. Hill and Milburn's data lead to $R_c \simeq 7$ ohmmeters.

The over-all resistivity of a dirty sand which contains oil may now be written. The reciprocal resistivity is:

$$\frac{1}{R_t} = \frac{f_c(1/R_c)(1/R_w)S_w a}{(1/R_w)d + (1/R_c)(1-d)} + bf_c^2(1/R_c) + c(1/R_w)S_w^2. \tag{3}$$

Here

f_c = fraction of solid framework of rock which is conducting

R_c = effective resistivity of clay when wet and in situ. Although not exactly a constant (because of Donnan effects) it is approximately so.

The magnitude of R_c is of importance in assessing the significance of equation (3). R_c has been determined by Patnode (1949) for Aquagel (bentonite) as 2.4 ohmmeters and by Berg (1951) for kaolin as 15 ohmmeters. No corresponding figure for illite seems to exist (one should be measured) but on the basis of relative cation-exchange capacities it should be about 9 ohmmeters. The value of 7 ohmmeters calculated from Hill and Milburn's experimental data is in good agreement with this estimate.

In practical cases R_w is less than one ohmmeter and the ratio $d/1-d$ exceeds five. Thus $(d/R_w)/(1-d)/R_c \geq 45$ if $R_c \simeq 9$.

Accordingly equation (3) may be simplified to:

$$\frac{1}{R_t} = \frac{f_c(1/R_c)S_w a}{d} + bf_c^2(1/R_c) + c(1/R_w)S_w^2 \tag{4}$$

$$= AS_w + \frac{BS_w^2}{R_w} + C. \tag{5}$$

where A, B and C are constants.

Equation (5) is a second-order polynomial; for any particular value of R_w it agrees with the expression derived intuitively by de Witte in his equation (8). De Witte next dropped the constant C on the grounds that it would normally be a very small term. This is generally justifiable since f_c, even though it can be as large as 0.31 (Figure 12) in extreme cases, appears as a squared term. In general it can be shown that $10 < A/C < 100$.

In cases of moderately dirty sands containing water of salinity corresponding to $R_w < 1.0$ ohmmeters it appears possible to disregard C in equation (5) and to write:

$$\frac{1}{R_t} = AS_w + \frac{BS_w^2}{R_w}. \tag{6}$$

Equation (6) is the equation derived by de Witte and used by him to make nomographed solutions to practical interpretation problems.

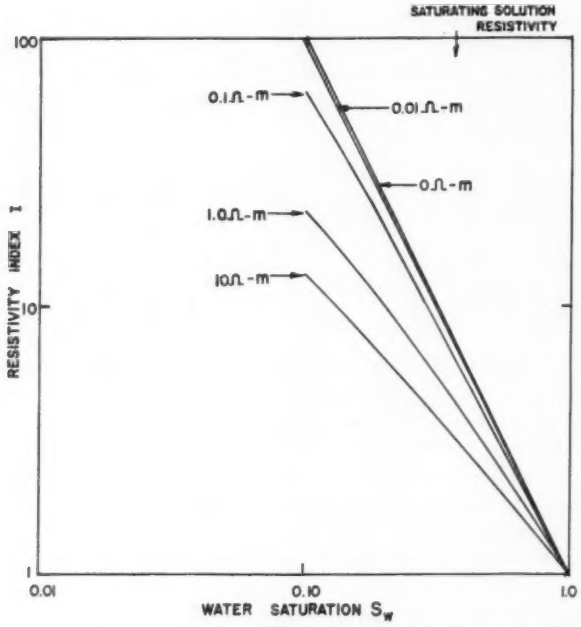


FIG. 13. Effect of resistivity of saturating brine on the resistivity index-saturation relationship of a dirty sand.

Figure 13 shows a plot of resistivity index vs saturation at various constant R_w's for the porous medium shown in Figure 10. As would be expected from the form of equation (3), the lines are curved for all finite values of R_w. However, it is apparent that if the slight curvatures which result when $0<R_w<1.0$ ohmmeter are ignored it might be concluded that the value of the resistivity index exponent n in $I=S_w^{-n}$ was decreasing as R_w increased. Physically this is not so; the form of the graphs is the result of the first two terms of equation (3) becoming relatively more important as R_w increases. Thus it is probable that the practice is entirely arbitrary of allocating to n a value lower than 2.0 when a sandstone is believed to contain clay. It is also difficult because the value to be selected is so dependent upon the relation between R_w and the other rock parameters. It seems preferable to make the standard assumption that n is 2.0 and to interpret the observed data by a scheme based on an understanding of the physical factors involved.

The calculation of the S.P. of a dirty sand is readily achieved by means of the model shown (Spiegler et al., 1956).

If equation (3) is written as $K_1+K_2+K_3$ where K_1 is the first term, K_2 the second and K_3 the third, the junction potential set up in the aggregate is:

$$E = E_m \frac{K_1 + K_2}{K_0} + E_J \frac{K_3}{K_0} = E_m(1 - f_J) + E_J f_J. \tag{7}$$

Here

$K_0 = K_1 + K_2 + K_3$

E_m = membrane potential $= RT/F \ln a_w/a_{mf}$

E_J = junction potential in a clean sand $= (2t^- - 1)RT/F \ln a_w/a_{mf}$

f_J = fraction of current carried by the aqueous component of the total conductivity

$$\text{S.P.} = E_c = E_m - E$$
$$= f_J(E_m - E_J)$$
$$= f_J \ 70 \log a_w/a_{mf} \text{ at room temperature.} \tag{8}$$

Thus the S.P. reduction factor α is given by:

$$\alpha = f_J = \frac{K_3}{K_0}. \tag{9}$$

Equation (9) and Figures 10 to 12 show that a given percentage clay is most effective in making α small when K_3 is also small, i.e. a given percentage clay causes α to be much smaller in a low-porosity sand than in a high-porosity one, other conditions being the same.

It is instructive to examine the S.P. and resistivity data for an unconsolidated dirty sand containing oil and to interpret these data by the Schlumberger charts, the method advocated by de Witte and the exact Schlumberger equation.[8] A comparison of this sort is given below.

Conditions:

$S_w = 0.10$ in all cases

$S_{xo} = 0.80$, i.e. 20 percent R.O.S. in all cases

$a_w/a_{mf} = 10$ in all cases

S.P. mv	α	R_{mf} Ohm-meter	R_w Ohm-meter	R_t Ohm-meter	R_{xo} Ohm-meter	R_{xo}/R_t	Saturation		
							de Witte Method %	Schlumberger Charts %	Calculated Schlumberger %
28.0	0.40	10	1.0	41.9	10.3	0.247	15	<0	4.4
51.8	0.74	1	0.1	17.4	2.62	0.151	11.5	4	7.1
66.5	0.95	0.1	0.01	2.76	0.422	0.154	10.5	8	9.5
70.0	1.0					0.156	10.0	10.0	10.0

As has been observed above, when R_w is below one ohmmeter the de Witte method gives the correct saturation within any reasonable limits. The Schlumberger results err more significantly. Note, however, that the de Witte method

[8] $S_w = S_{xo}[(R_{xo}/R_t)^{1/\alpha}(R_w/R_{mf})]^{1/2}$

gives somewhat higher saturations than are correct, while the Schlumberger method gives rather lower ones. It is pertinent here to observe again that the Schlumberger method is correct when applied to the physical situation for which it was derived, i.e. interlaminated clean sand and clay. The greater error obtained using the routine Schlumberger charts reflects assumptions built into them to facilitate their use.

Which method is best used in routine interpretation? The answer seems to depend on the answer to a further question. Do natural dirty sands generally consist of interlaminated clean sand and shale, sand with interstitial clay or interlaminations of shale with sand containing interstitial clay? It can be said that all laboratory data concerned with dirty sands (see Hill and Milburn [1956] for example) strongly indicate the presence of interstitial clay, i.e. a plot of $1/R_o$ vs $1/R_w$ is curved as $1/R_w \rightarrow 0$ and the value of $1/R_o$ at $1/R_w = 0$ is small. For interlaminated sands and shales the plot of $1/R_o$ vs $1/R_w$ should be a straight line with a finite intercept at $1/R_w = 0$ equal to the parallel conductivity of the clay. But the data that appear in published papers are taken in the course of experiments made using rather small cores. Furthermore the cores used are not selected at random from an interval as statistically speaking they should be. For reasons of human fallibility they tend to be chosen because of their sandiness and probable possession of permeability. They are inherently biased samples. The correct answer to the question concerning the typical form of the clay content of a productive sandstone interval needs a basis of more detailed study in the field. It is the writer's view that, from a geological standpoint, neither interlaminated clean sand and shale nor uniformly disposed interstitial clay is the most typical form. It seems more probable that where clay is disposed interstitially in a sand there will be intervals where the clay content is sufficiently heavy to justify the term shale being used. If this is so it seems wise to use both the de Witte and Schlumberger systems of interpretation to put bounds upon the apparent water saturation and, hence, productive possibilities of a sand. The porosity of the sand should also be roughly estimated by the use of both techniques.

CONCLUSIONS

It is evident from the length of the foregoing (and from its incompleteness) that many unsolved problems and many difficulties are still associated with the interpretation of logs made in sandstone formations. The writer has been idiosyncratic; he has devoted most space to those topics with which he has some personal familiarity. These topics are important but others of almost equal significance have not been touched on. Amongst these are: the quantity of residual oil which remains unflushed by invading filtrate and its relation to rock structure, surface wettability and filtrate composition, the probability that in gas-bearing sandstones gravity segregation of filtrate occurs with the filtrate moving *down* towards a permeability barrier, the relationship between observed gravity segregation and the actual permeability of a formation, and methods for the estima-

tion of permeability from log records generally. The last remains a problem to which, in spite of some gallant attempts, no general solution has yet been proferred.

It would be unwise to exaggerate these problems and to conclude that the interpretation of sandstones is presently in a parlous state. As was observed in the introduction to this paper, a high percentage of sandstones can now be interpreted qualitatively or semi-quantitatively. It remains a matter for philosophic discussion whether rigorous quantitative interpretation will ever be possible or, indeed, will ever be really required. It is much more important to note that within the last decade the refinement of electric logging equipment and the development of new instruments (e.g. velocity log, density log, nuclear magnetic resonance log) have provided both more reliable as well as entirely novel and independent rock parameters. These developments have in their turn stimulated research on the physical significance of the parameters measured. As the significance of the new parameters was elucidated so have formal organizations been set up within oil companies to make practical use of the new knowledge. It can safely be said that all these developments have decreased by at least a factor of two the probability of overlooking a productive sandstone. It can be said with certainty that this favorable trend will continue in the future.

ACKNOWLEDGMENTS

The writer is indebted to Messrs. G. H. F. Gardner, J. Downie and A. R. Gregory for the new experimental data contained in this paper and to Dr. Gardner for making a theoretical check of the experimental data concerning the low zone.

REFERENCES

Berg, J. W., 1951, Mineral Industries Experiment Station Bull. No. 59, Pennsylvania State University, p. 1–7.

Campbell, W. M., and Martin, J. L., 1955, Displacement logging—a new exploratory tool: Trans. A.I.M.E., v. 204, p. 233–239.

Chaney, P. E., Mayes, F. M., Bennett, John, and Jones, J. W., 1959, New slim logger runs through drill pipe: Oil & Gas Jour., v. 57, p. 112–113, April 13, (Condensation of paper titled "Drill-stem logging tool" presented at 1959 spring meeting of Southern Dist., API Div. of Prod., New Orleans.)

de Witte, A. J., 1957, Saturation and porosity from electric logs in shaly sands: Oil & Gas Jour., March 4 and April 15.

——— 1957, Influence of differential displacement in invaded oil and gas sands on the induction log: J. Pet. Tech., June, p. 48–50.

Doll, H. G., 1950, Selective S.P. logging: Trans. A.I.M.E., v. 189, p. 129–142.

——— 1950, The S.P. log in shaly sands: Trans. A.I.M.E., v. 189, p. 205–214.

Gondouin, M., and Scala, C., 1958, Streaming potential and the S.P. log: Trans. A.I.M.E., v. 213, p. 170–179.

——— Tixier, M. P., and Simard, G. L., 1957, An experimental study of the influence of the chemical composition of electrolytes on the S.P. curve: Trans. A.I.M.E., v. 210, p. 58–72.

Hicks, W. G., 1958, Lateral velocity variations near boreholes: Presented at 28th Annual Meeting of the Soc. of Explor. Geophys., San Antonio, Oct. 15.

Hill, H. J., and Milburn, J. D., 1956, Effect of clay and water salinity on electrochemical behavior of reservoir rocks: Trans. A.I.M.E., v. 207, p. 65–72.

——— Anderson, 1959, Streaming potential phenomena in SP log interpretation: Trans. A.I.M.E., v. 216, p. 203.

Kimura, M., 1957, Effective thermal conductivity of packed beds: Soc. of Chem. Eng. (Japan), v. 21, p. 471–480.

McKelvey, J. G., Southwick, P. F., Spiegler, K. S., and Wyllie, M. R. J., 1955, Application of a three-element model to the S.P. and resistivity phenomena evinced by dirty sands: Geophysics, v. 20, p. 913–931.

——— Spiegler, K. S., and Wyllie, M. R. J., 1959, Ultrafiltration of salt solutions through ion-exchange membranes: Chem. Eng. Progress Symposium Series, v. 55, p. 199–208.

Patnode, H. W., 1949, Relationship of drilling mud resistivity to mud filtrate resistivity: Trans. A.I.M.E., v. 186, p. 14–16.

Perkins, F. M., Brannon, H. R., and Winsauer, W. O., 1954, Interrelation of Resistivity and Potential of reservoir rock: Trans. A.I.M.E., v. 201, p. 176–181.

Poupon, A., Loy, M. E., and Tixier, M. P., 1954, A contribution to electrical log interpretation in shaly sands: Trans. A.I.M.E., v. 201, p. 138–145.

Raimondi, P., Gardner, G. H. F., and Petrick, C. B., 1959, Effect of pore structure and molecular diffusion on the mixing of miscible liquids flowing in porous media: Presented to the Am. Inst. Chem. Eng., San Francisco, Calif., Dec. 8. (In press.)

Rust, C. F., 1952, Electrical resistivity measurements on reservoir rock samples by the two-electrode and four-electrode methods: Trans. A.I.M.E., v. 195, p. 217–224.

Sauer, M. C., Southwick, P. F., Spiegler, K. S., and Wyllie, M. R. J., 1955, Electrical conductance of porous plugs: Ind. & Eng. Chem., v. 47, p. 2187–2193.

Schlumberger Well Surveying Corp., 1958, Introduction to Schlumberger well logging: Document n. 8, p. 38–39.

Segesman, F., and Tixier, M. P., 1959, Some effects of invasion on the S.P. curve: Trans. A.I.M.E., v. 216, p. 138–146.

Spiegler, K. S., Yoest, R. L., and Wyllie, M. R. J., 1956, Electrical potentials across porous plugs and membranes: Disc. of the Faraday Soc., n. 21, p. 174–185.

Tixier, M. P., Alger, R. P., and Doh, C. A., 1958, Sonic logging: Presented at the A.I.M.E. Meeting, Houston, Tex., October 16. Preprint n. 1115-G.

Worthington, A. E., and Meldau, R. F., 1958, Departure curves for the self-potential log: Trans. A.I.M.E., v. 213, p. 11–16.

Wyllie, M. R. J., 1949, A quantitative analysis of the electrochemical component of the S.P. curve: Trans. A.I.M.E., v. 186, p. 17–26.

——— 1954, Ion-Exchange membranes, I-Equations for the multi-ionic potential: J. Phys. Chem., v. 58, p. 67–73.

——— 1955, Role of clay in well log interpretation: State of Calif. Bull. 69, p. 282–305.

——— de Witte, A. J., and Warren, J. E., 1958, On the streaming potential problem in well logging: Trans. A.I.M.E., v. 213, p. 409–417.

——— and Gardner, G. H. F., 1958, The generalized Kozeny-Carman equation: World Oil, March and April.

——— Gregory, A. R., and Gardner, G. H. F., 1958, An experimental investigation of factors affecting elastic wave velocities in porous media: Geophysics, v. 23, p. 459–493.

——— Gregory, A. R., and Gardner, L. W., 1956, Elastic wave velocities in heterogeneous and porous media: Geophysics, v. 21, p. 41–70.

——— and Southwick, P. F., 1954, An experimental investigation of the resistivity and S.P. phenomenon in dirty sands: Trans. A.I.M.E., v. 201, p. 43–56.

GEOPHYSICS, VOL. XXV, NO. 4 (AUGUST, 1960), PP. 779–853, 23 FIGS.

WELL LOGS IN CARBONATE RESERVOIRS*

L. G. CHOMBART†

ABSTRACT

Modern well logs can play an important, often decisive role in the evaluation of carbonate reservoirs, and in well completions therein. To do so however, the logs must be selected and interpreted with due regard for the specific rock "types" and pore structures encountered by each well.

Indeed, the basic condition stated applies to all evaluation and completion techniques now in use or conceivable. It becomes vitally important in carbonate reservoirs, however, because of their extraordinary heterogeneity. Characteristically, these reservoirs exhibit significant, often extreme, and always unpredictable variations in pore structure, pore size distribution and fluid content, within very short distances, in any direction.

To cope with such a reservoir, an evaluation and logging program adhering to certain principles is most likely to yield valid results and insure better completions and greater ultimate recovery, at minimum cost. First, in every well, the cuttings or cores should be described precisely as to rock types and depths. Second, any techniques used should permit the largest possible number of determinations through the reservoir, so that any existing relationships between pore size distribution, porosity and water saturation may be established on a sound statistical basis. Among logging devices, "focusing" tools meet this requirement best. Third, starting very early in the development of the reservoir, the latter should be cored and logged in key wells, the cores subjected to capillary pressure and other petrophysical tests, and all potentially diagnostic logs run and analyzed in the light of all other data. Fourth, in non-key wells, the logging program should include only those logs proved most reliable in the key wells for the pore structures encountered and the data desired (usually porosity, water saturation, net ft of pay).

INTRODUCTION

The objective assigned to this paper was a summary of the present status of well logging and log interpretation techniques in carbonate reservoirs.

In line with a long-held conviction, however, doing justice to the stated objective and to the interest it might elicit at the Symposium clearly required that the subject be broadened somewhat to show how and where logs and log analysis fit in the entire evaluation program in a carbonate reservoir. The paper represents an attempt in that direction. In the process it seizes the opportunity to restate some of the compelling reasons why carbonate reservoirs, more than any others, demand the complete, active cooperation of all those involved in their discovery, evaluation and exploitation.

Even without thus placing the subject in its natural setting, it was found necessary to allude to the pore structure, pore size distribution and fluid distribution of reservoirs so often and to such an extent that a brief review of these characteristics appeared desirable, or at least forgivable, for the benefit of those who might not be intimately familiar with them. Such a review is offered in Part I. Section IA exposes the characteristic heterogeneity of the pore structure of carbonate rocks. Section IB briefly explains what effects this heterogeneity has on the fluid distribution in the reservoir space. Section IC concludes Part I by pointing to the pore size distribution, the total porosity and the water saturation

* Presented at the 29th Annual Meeting of the Society, November 11, 1959.

† Consultant, Wichita, Kansas.

as the elements best suited to the volumetric evaluation of a carbonate reservoir, and by listing the four techniques capable of yielding one or more of these elements: capillary pressure tests, analysis of cores cut with water-base mud, analysis of cores cut with oil-base mud, and well log analysis. Those readers who are fully conversant with these topics, will, of course, want to proceed immediately to Part II.

Part II advocates a dual statistical approach as the best, not to say the only way, to cope with heterogeneous reservoirs, whatever the techniques used, comprising identification and classification of the pore structures encountered in each well (Section IIA), and quantitative determinations (Sections IIB and IIC).

Part III deals with the contribution of logging techniques and comprises four parts: IIIA resistivity-fluid content relationships in clean carbonate reservoirs; IIIB fundamental generalities on the suitability of logs for statistical evaluation work; IIIC elements for the design of logging programs for carbonate reservoirs, and for the use of the resulting logs; IIID limitations of log analysis due to heterogeneity.

Finally, Part IV, using all that went before, presents certain conclusions on the role played by well logs, and certain thoughts that guide the planning of a logging and volumetric evaluation program suitable for a carbonate reservoir.

CONVENTION

The reservoir data obtained through the determinations made in core analyses, capillary pressure tests, log interpretations, are essentially all volumetric data, such as porosity, permeability, water saturation, fluid contacts, net porous-permeable thickness, net pay thickness, or volumetric information, such as pore size distribution. These techniques, then, are the tools used for the volumetric evaluation of a reservoir. Other techniques supplying equally important data, such as pressure, temperature, damage to the well bore, probable extent of reservoir, rates of flow, etc. also must be called on in the complete evaluation of a reservoir.

This paper deals exclusively with volumetric evaluation techniques. For the sake of brevity, the single word "evaluation" will almost always be used in the text.

DEFINITIONS

Pore Structure is a fundamental characteristic of a rock. It refers to the organization and geometry of the pore space in that rock. It is determined by the composition and texture of the rock. Composition refers to the mineralogical or chemical constituents of a rock. Texture refers to the sizes and shapes of the particles, grains or crystals making up the rock, and the manner in which they are assembled.

Pore Size Distribution is that feature of pore structure which refers to the distribution of the pore space among the various sizes of the pores, interstices,

fissures, and fractures present in that pore space. The size of a pore or an interstice or a vug may be expressed in terms of its maximum and minimum dimensions, or of its average or median dimension. The size of a fissure or a fracture refers to the width of the fissure or fracture.

Unless otherwise specified, pore structure and pore size distribution are considered to be observed at some macroscopic scale, stated or implied by the context.

Formation Type, or *Rock Type* is meant here in the sense defined by Archie of a formation "whose parts have been deposited under similar conditions and have undergone similar processes of later weathering, cementation and resolution." Essentially, therefore, formation type and pore structure refer to the bulk volume and the pore space, respectively, of the same geological entity, or a part thereof.

PART I. PORE STRUCTURE AND FLUID DISTRIBUTION IN CARBONATE RESERVOIRS

IA. THE PORE STRUCTURE OF CARBONATE ROCKS

Carbonate reservoirs or more generally, carbonate sediments, are characterized by the extraordinary, unpredictable heterogeneity of their pore structure. This heterogeneity is a prominent feature at any scale of observation used, and has many far-reaching consequences, some of which fall within the scope of this paper.

Thus a prerequisite to the subject is at least a general understanding of the origin, development and essential characteristics of such a complex pore structure. In addition, for reasons which will appear only in Part III, it is most helpful to contrast this pore structure and that of sandstones. This may best be done by disposing of the latter first.

Pore Structure of Sandstones

As well-known sands and sandstones belong to the class of clastic or detrital sediments, the other important members of which are clays and shales, silts and siltstones, conglomerates and breccias. They are made of more or less closely packed fragments, particles or grains of pre-existing rocks brought from some source area to the site of their deposition. In the Wentworth classification, the grains in a pure sand range in their greatest dimensions from 1/16 of a mm, maximum size of silt particles, to 2 mm, minimum size of conglomerate and breccia particles. For the purposes of this paper, only "clean" sands, that is sands essentially devoid of shaly or colloidal material, need be considered.

The pore structure of the highly developed intergranular pore space formed by the myriads of interconnecting spaces not occupied by solid particles is obviously determined by the sizes and shapes of these particles, and by the relative proportions of the various sizes present, that is, the grain size distribution. Wherever these determining factors remain the same, a stratum layer of macro-

scopically homogeneous pore structure and pore size distribution results.[1] Subsequent compaction, precipitation of cementing material in the pore space, or deposition of extraneous fine material in the pore space, will not fundamentally alter the homogeneity of such a layer.

A sand body may be considered as composed of a certain number of homogeneous layers as above defined, juxtaposed along the surfaces of stratification, piled over one another in depth, each layer corresponding to slightly different conditions of deposition. The changes from layer to layer rarely occur abruptly but most often are gradual. This is particularly true of changes occurring along the stratification.

Obviously, a homogeneous layer in the sense defined can have most any dimensions, areally and in thickness. However, it is generally permissible to assume that it preserves its homogeneity radially from a borehole which has penetrated it, beyond the "reach," or "radius of investigation" of the largest logging devices used today. The importance of this observation will become clear in Part III.

Pore Structure in Carbonate Rocks

Carbonate rocks belong to the class of non-clastic sediments[2] in which the elementary components are particles or crystals originally derived at or very near their site of deposition by various physico-chemical or biological agencies, from material floating or in solution in natural waters, and diagenetically altered by other physico-chemical or biological agencies. Original floating material included living organisms of various types as well as any fragments of pre-existing rocks that were present at the time. (Clastic fragments therefore often enter in the composition of non-clastic rocks.)

The most important carbonate rocks, and the only ones discussed in this paper, are limestones and dolomites. Roughly, they are rocks containing more than 50 percent of the minerals calcite (pure calcium carbonate), and dolomite (double carbonate of calcium and magnesium), respectively. It should be noted that all dolomites, other than evaporite dolomites, were once limestones and are the result of a gradual replacement of calcite molecules in the latter by an equal number of dolomite molecules.

In carbonate rocks (and more generally in non-clastic sediments), distinction is made between "primary" and "secondary" pore structures.

Primary Pore Structure

Primary pore structure is that found in a carbonate rock whose constituent

[1] This macroscopic homogeneity is never perfect isotropy, but normally is more pronounced in a surface parallel to the stratification (bedding plane) than in a direction perpendicular to it. Of course, at the microscopic scale, the pore geometry may and usually does change appreciably from pore to pore, even in a surface of stratification in a well sorted sand.

[2] Siliceous rocks, such as cherts, are another important member of this class. Most of the statements on well log interpretation made in this paper apply to them as well.

particles or crystals have been subjected only to compaction, lithification, or simple plugging of some of the pore space by materials which cemented or deposited themselves therein. Thus defined, primary pore structure occurs only in limestones and evaporite dolomites. The latter occurrence is a rare case, and will not be discussed further.

The primary pore structure in limestones should resemble that of a clastic sand of similar grain size. It does, except in two relatively minor respects. First, clastic rocks essentially have a so-called fragmental texture, resulting from the rather loose settling upon one another of irregular particles, many of them broken or abraded during their transportation to the site of deposition. By contrast, carbonate rock matrices primarily exhibit a crystalline texture in which the constituent particles are mostly interlocked or imbricated assemblages of crystals. Second, the primary porosity of carbonates usually is more affected by cementation than the porosity of clastic rocks of similar particle size.

The porosity-permeability development, or P.P.D. for short, of limestones having only primary porosity will of course depend upon the nature and size of the elementary particles or crystals. Oolites, which are made of small egg-shaped limestone grains formed by precipitation of calcite around nuclei in strongly agitated, shallow waters, have very much the same porosity and permeability characteristics as sands made of medium size, round grains. They often constitute excellent reservoirs and producers. At the other extreme, very finely crystalline limestones are very compact, have very little porosity and practically no permeability. Very generally, as will be seen in Part IIB, they cannot contain hydrocarbons under any normal reservoir conditions. Chalk, a soft limestone composed of very fine biological forms and calcite, is still a different case. It has a high primary porosity, but usually negligible to very low permeability, and is rarely productive.

Secondary Pore Structure

Non-clastic rocks seldom preserve their primary pore structure and P.P.D. absolutely intact. Instead, in the great majority of cases, the rocks acquire secondary pore structure and P.P.D., subsequent to lithification, through one or more of three main diagenetic processes: solution action, jointing and/or fracturing, and dolomitization.

Solution action refers to the dissolution of portions of a carbonate rock by ground water solutions charged with carbon dioxide and organic acids. Its initiation predicates the existence of a continuous pore network, be it primary porosity or joints or fractures, connecting the source of ground waters with the rock attacked and allowing ionic diffusion. It continues as long as new or undersaturated water is supplied, or diffusion takes place. The end result obviously is an increase in the total porosity of the rock, at the expense of its original constituents. The voids which it creates can vary extremely in sizes and shapes, ranging from pin-point holes to irregularly-shaped vugs to cavern-sized cavities.

Joints, fractures and fissures caused by contraction during lithification, or

crustal movement, or mineralogic change, play a double role in the development of secondary porosity: their very occurrence creates additional pore space, and moreover provides the most important and easiest means by which waters can gain access to the innermost parts of stratified carbonate rocks and through which ionic diffusion may take place. In this respect, most carbonate rocks are innately rigid, thus fortunately prone to develop joints and fractures.

Dolomitization occurs when magnesium-rich waters circulate through the pore space of a limestone, causing a gradual replacement of calcite molecules by an equal number of dolomite molecules. Since the latter occupy only .88 times the volume of the former, a net increase in porosity ideally results.

Any secondary pore space subsequently can be altered or reduced, sometimes

TABLE I. COMPARISON OF THE POROSITY AND PERMEABILITY OF A CONSOLIDATED SANDSTONE AND A CAVERNOUS LIMESTONE

Sandstone		Limestone	
Permeability, Millidarcys*	Porosity, Percent	Permeability, Millidarcys*	Porosity, Percent
2,650 H	26.1	150	27.5
6,300 H	29.6	1,850	6.5
2,400 H	25.8	1,520,000	26.0†
450 V	23.4	<0.1	7.0
1,100 V	25.7	<0.1	5.5
620 H	26.1	2,670,000	36.5†
Average 2,250	26.1	699,000	18.2

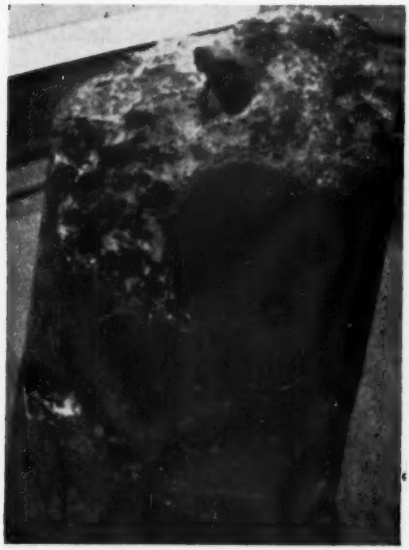
* H = Permeability measured parallel to the bedding plane.
V = Permeability measured perpendicular to the bedding plane.
† Volume of cavernous conduit was included in the total void volume.
After A. C. Bulnes and R. U. Fitting, reference cited.

completely eliminated, by the deposition of crystals of one mineral or another, calcite being the most frequent offender.

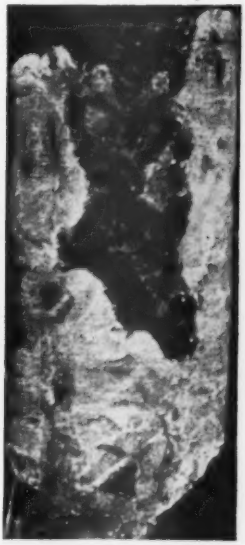
Figure 1 shows photographs of 4-inch diameter cores recovered at four different localities in the State of Michigan, from the pay zone in the Trenton-Black River formation of Ordovician age. The primary rock is a limestone with very little porosity. Fracturing, solution action and dolomitization all contributed to the secondary porosity in the pay zone. In the Northville core, considerable refilling of the secondary porosity by white crystalline dolomite has taken place.

Table I, taken from a major early contribution to the subject by Bulnes and Fitting, compares the porosities and permeabilities of two groups of conventional core plugs, one inch long and $\frac{3}{4}$ inch in diameter, taken at random from two cores of about the same bulk volume, one from a Gulf Coast sandstone, the other from a fragment of cavernous limestone. As these authors point out, the sandstone evidently was not homogeneous, but it was "not unreasonable to suppose" that values representative of the average porosity and permeability of the sandstone as a whole could be obtained through simple averaging of the porosities and permeabilities measured on any small group of plugs, irrespective of the number

SCIPIO.



ALBION.



NORTHVILLE.

PULASKI.

FIG. 1. Trenton—Black River formation.

of the latter, or their size, shape and orientation with respect to the bedding planes. It was understood, of course, that the plugs should be large in relation to the grain size. On the contrary, such averaging of the values measured on the limestone plugs could not be expected to yield valid or even meaningful averages. The plugs were too small in relation to some of the vugs and the results obtained are critically dependent upon the size, shape and pore structure of each individual plug, as well as the direction of each measurement. Such observations led to the application of statistical methods to core analysis in heterogeneous sandstones and carbonate rocks, and to the development of full diameter core analysis. At least one major requirement for the evaluation of carbonate reservoirs through core analysis or any other method is also seen to emerge: in such reservoirs, any measurement must be interpreted with due regard for the specific rock type and pore structure included in, as well as the specific geometry of, the measurement.

Another way to illustrate the heterogeneity of carbonate rocks of course is to compare core analyses or well logs in offset wells. Figure 2 shows some of the curves of the logs obtained in four wells in the Nichols pool, Kiowa County, Kansas. The reservoir is of Mississippian age and its matrix is essentially made of various types of cherts, (some fresh or vitreous, some tripolitic), crystalline and chalky limestone, dolomitic chert and dolomite, with shaly or colloidal material present in streaks or in dispersed form. In addition, the reservoir rock appears to give some evidence of being naturally fissured and fractured. The variations in matrix type and pore structure are totally unpredictable and correlation lines corresponding to a given geological time can rarely be drawn with any certainty or over wide areas.

Figure 3 reproduces the cross section of the limestone and dolomite reservoir of Parentis, France, as presented in a paper given at the 5th World Petroleum Congress in New York.

IB. EFFECTS OF PORE STRUCTURE ON THE FLUID DISTRIBUTION IN A CARBONATE RESERVOIR PORE SPACE

Pore structure and pore size distribution profoundly influence not only the porosity and permeability, but also the fluid distribution of a reservoir, that is, the manner in which the reservoir fluids distribute themselves through the reservoir pore space. This latter influence must be understood in its broad features at least, if a reservoir, especially a carbonate one, is to be properly evaluated. In turn, this requires an elementary knowledge of the physical laws which govern the accumulation of oil and gas in a reservoir, following their migration thereto.

Physical Laws Governing the Fluid Distribution in a Reservoir Pore Space

The fluid distribution considered here is that prevailing in a reservoir at each well at the time the latter is drilled. For the discovery well it is that of the untapped or virgin reservoir at that well. For subsequent wells it may or may not be the virgin distribution prevailing around these wells, but should normally be close to it if the field is being rapidly developed.

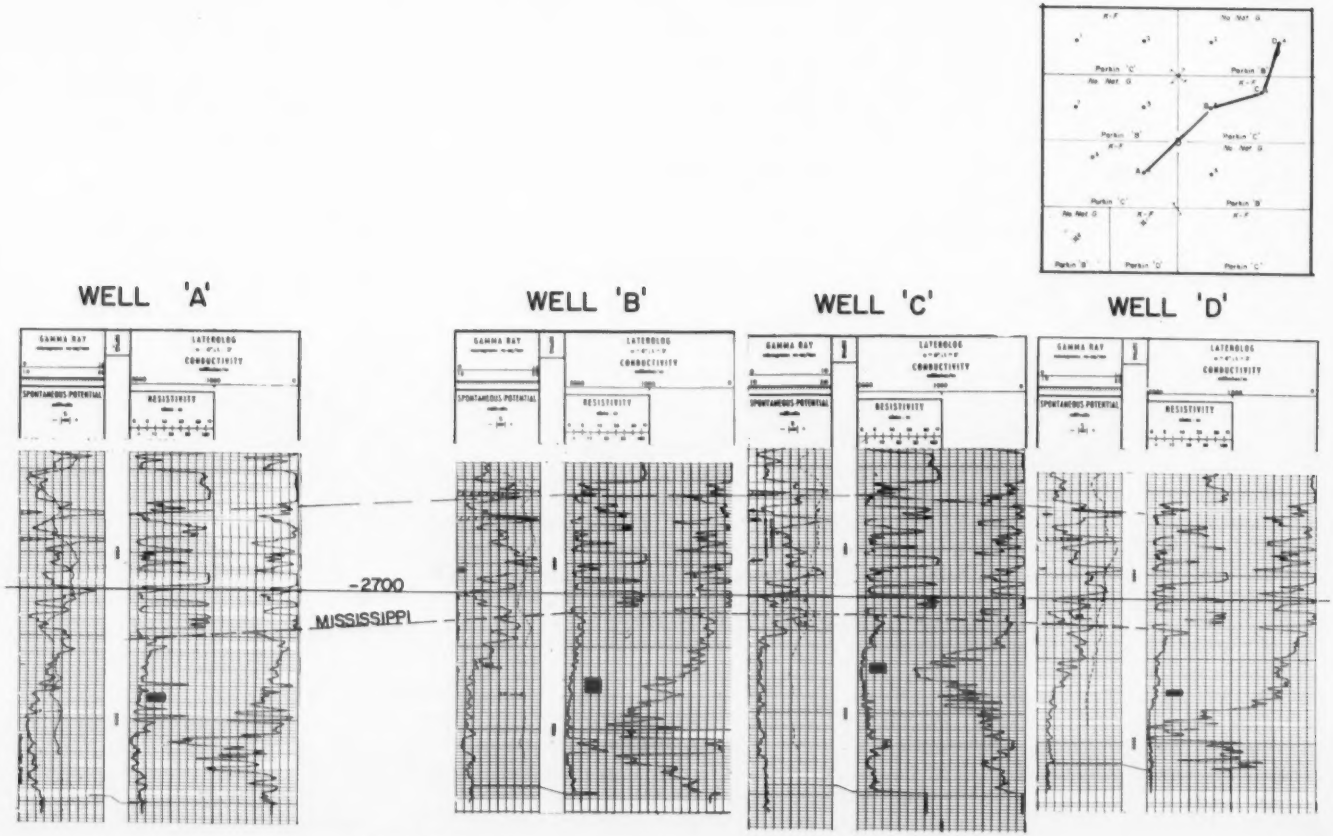


FIG. 2. Heterogeneous carbonate and siliceous rocks, Nichols Field, Kansas.

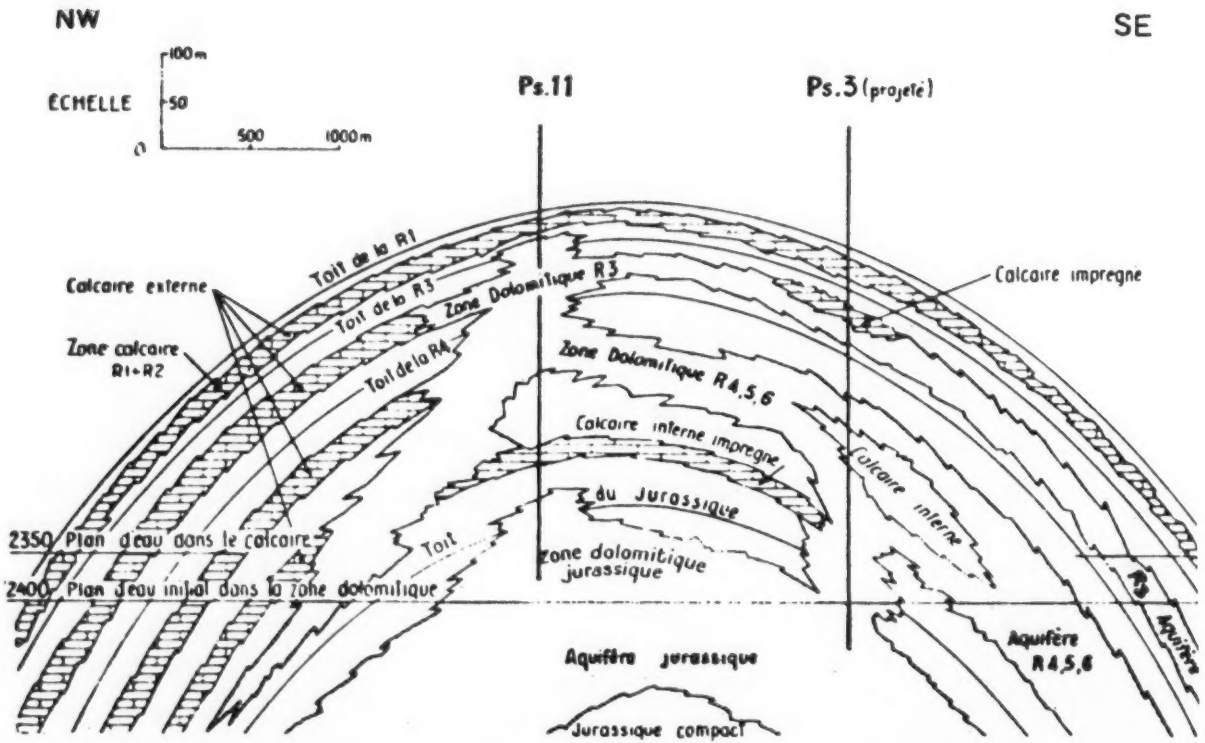


FIG. 3. Schematic cross section of main pore structures in Parentis Field, France. (After Chueca.)

It is now generally accepted that the pore space of every reservoir was originally filled with connate or interstitial water; that the hydrocarbons it contains today migrated therein and forced some of the water out in ages past, through a combination of favorable circumstances and conditions; and that these essentially immiscible fluids most generally reached their final equilibrium distribution within the core space long before their discovery.

If one excludes the fascinating but more complex instances where hydrodynamic forces play an active role the distribution under study results from the equilibrium reached in the past between only two opposing groups of hydrostatic forces.[3] The first consists of the gravitational forces acting on the fluids as a result of the differences in their specific densities. Had these been the only acting forces, the fluids would over geologic times have segregated themselves completely (for all intents and purposes) from one another, the top and lower parts of the reservoir pore space being occupied only by gas and oil, respectively, and the interstitial water having moved bodily out of the reservoir proper. However, the interfacial tensions arising in the myriads of immiscible fluid interfaces which the migration caused to appear in the pore space brought the gravitational segregation to an eventual standstill.

The mechanism through which such an equilibrium is attained has been the object of numerous theoretical and experimental studies. The familiar elementary experiment, shown in Figure 4, of the water rising in a capillary glass tube of small diameter, used as a starting point in many of the studies, will serve this purpose here as well. In spite of its density, the water rises in the tube a height h above the free water level L in the large tank. It is seen that the pressure P_A at point A just above the interface air-water in the tube exceeds the pressure P_B at point B just below the interface, by a quantity:

$$P_A - P_B = (P_L - hd_a g) - (P_L - hd_w g) = h(d_w - d_a)g, \qquad (1)$$

where P_L is the pressure at the free water level L, d_w and d_a are the specific densities of the water and air, respectively, and g is the gravitational constant. The difference $P_A - P_B$ is called the capillary pressure P_c across the interface. It is positive on the concave side of the interface or meniscus.

In the same experiment it is further observed that the self-elevated interface is curved. This curvature is due to the air-water interfacial tension T_{wa} arising in the interface as a result of the immiscibility of the fluids. It was found by Laplace to be related to P_c, thus:

$$P_c = T_{wa}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = T_{wa}C, \qquad (2)$$

[3] A third group of forces, namely forces of friction played a part during the migration of the petroleum in the reservoir and during the period in which the fluids reached their final distribution. However, these friction forces gradually decreased to the vanishing point as the reservoir reached its condition of static equilibrium.

where R_1 and R_2 are the principal radii of curvature of the interface, and C is the mean curvature.

The radii R_1 and R_2 are related to the radius r of the tube. If r is small enough, the interface is practically a spherical segment, so that $R_1 = R_2 = r/\cos\theta$, θ being the "contact angle" between the liquid surface and the glass surface. For water the angle θ is actually zero, that is, the meniscus is a hemisphere. Equation (2) may then be written:

$$P_c = 2T_{wa}/r = T_{wa}C. \tag{3}$$

By equating (1) and (3), which both express P_c, one obtains:

$$P_c = T_{wa}C = 2T_{wa}/r = h(d_w - d_a)g. \tag{4}$$

Thus, and as observed in practice, the height to which the meniscus rises is inversely proportional to the radius of the tube.

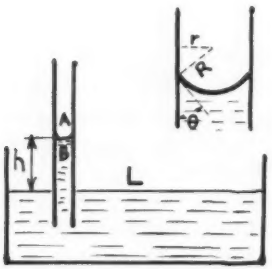
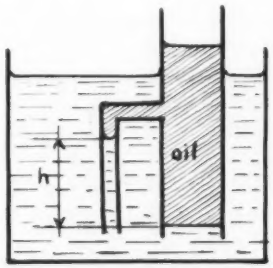


FIG. 4.



(after Houpeurt)

FIG. 5.

Figure 5 shows another simple experiment, suggested by Houpeurt, where oil and water stand in equilibrium in a capillary tube. Then:

$$P_c = T_{wo}C = 2T_{wo}/r = h(d_w - d_o)g, \tag{5}$$

where h is the height of the oil-water interface above that in the large oil column, d_o is the specific density of the oil and T_{wo} is the interfacial tension for the oil and water used. Again, the smaller the tube diameter, the higher the height to which the meniscus rises. (In fact, even though T_{wo} is generally less than half T_{wa}, the height to which water rises will be considerably greater than that observed in the water-air experiment, for tubes of equal diameter, because the difference $d_w - d_o$ is much smaller than the difference $d_w - d_a$).

The behavior of the immiscible fluids in the above experiments may be explained by the fact that the glass tube is preferentially wetted by water. When several immiscible fluids are present in a pore space, that which adheres to or wets the solid walls of a pore space is called the "wetting phase." As well known,

water is most generally the wetting phase in sandstones and carbonate reservoirs, and wets their solid surfaces so completely as to make the contact angle θ equal to zero.

Figure 6, reproduced from Leverett, shows just a pair of contiguous, water-wet spherical sand grains of equal diameter, belonging to a hypothetical reservoir containing oil and water. The water forms a circular ring around the contact

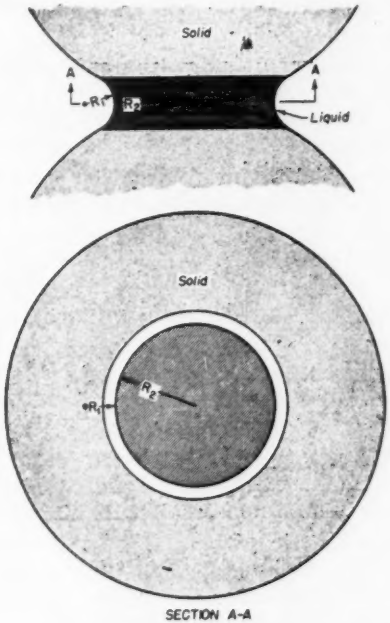


FIG. 6. Accumulation of liquid at contact point between spherical grains. R_1 rotates in plane of paper in upper view. R_2 rotates in plane of paper in lower view. (After Leverett.)

point, whose triangular half-cross section is defined by the spheres and by the curved oil-water interface, which is convex towards the water phase. The very same expression cited before holds for the interface in this system:

$$P_c = T_{wo}C = T_{wo}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = h(d_w - d_o)g, \tag{6}$$

R_1 and R_2 this time being the radii shown on Figure 6 and h being the height of the contact point between the grains, above the "zero capillarity level" or "free liquid level." As will be seen shortly, this horizontal level, where by definition both the capillary pressure and the oil-water interface curvature are nil, is

actually located below the lower boundary of the reservoir (assuming d_w greater than d_o).

Equation (6) states that the curvature of an interface is thermodynamically tied and directly proportional to the height of the latter above a reference level and to the capillary pressure across it. On the other hand, as pointed out by Leverett, the curvature is also a geometric quantity determined by the size and geometry of the particular interstice in which the interface is located, and by the fraction of the interstice space occupied by the water phase, that is, the water saturation in the interstice.

Consideration of equation (6) and Figure 6 allows a simple if somewhat crude demonstration of this fact, and leads to some important conclusions:

(a) The curvature increases with the height of the interface in the reservoir. The corresponding decrease in the radii R_1 and R_2 can be obtained only through the water ring of Figure 6 shrinking in volume, towards the contact point of the two grains. Thus, the water saturation S_w in a reservoir of homogeneous pore structure and pore size distribution must decrease continually from a maximum value at the base of the oil-bearing zone to a minimum value at the top. (As will be seen later, the maximum value depends in part upon the manner in which the migrating oil and the displaced interstitial water traded places in the lower part of the reservoir.)

(b) The minimum water saturation cannot fall below an "irreducible" value, first reached at the level where all the water rings at the contact points between grains have shrunk to such an extent that only a film of immovable water (at most a few molecules thick) remains on the portions of the grain surfaces not covered by the rings. This is called the pendular ring distribution.

(c) Obviously, the water saturation at each level of a reservoir must depend, among other things, upon the thickness of the reservoir and the amount of oil that migrated into the latter, i.e., it depends upon the distance to the free water level. Thus, one should not expect the irreducible water saturation to be attained in every reservoir one encounters.

Capillary Pressure-Water Saturation Curves

Because of the complexity of the pore structure and pore size distribution of natural reservoirs, the relationship among P_c or h or C on the one hand, and S_w and the pore size distribution on the other, can be determined only through "capillary pressure tests" made on cores or plugs (sometimes referred to as samples) of the reservoir rock. In these tests, the sample, previously saturated with a wetting fluid, is gradually "desaturated" through the injection of a non-wetting fluid under a pressure differential. In the "restored-state" method, the core is saturated with water (wetting fluid) and usually desaturated by injection of air or gas (non-wetting fluid). In the mercury injection method, the core is evacuated, then subjected to injection of mercury (non-wetting phase). The mercury injection method permits much more rapid determinations than the

restored-state method. Except for the difference in the proportionality coefficients applied to the P_c values, the curves obtained by both methods are practically identical.

In a test, the pressure is increased by steps and equilibrium (normally) is allowed to take place each time. Means are provided for the simultaneous measurement of the capillary pressure and one of the following: water saturation (by resistivity measurement, in the restored-state method), or volume of wetting fluid ejected from the sample (restored-state method) or volume of mercury injected in the sample.

For each sample studied, the data obtained are plotted in a linear co-ordinate

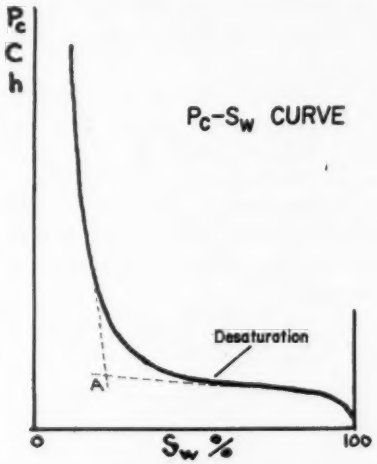


FIG. 7.

system, the capillary pressures as ordinate, and the water saturations, or the ratios of the volume injected or ejected, as the case may be, to either the bulk volume or the pore space volume of the sample, as abscissae. (Either type of ratio, of course, can readily be translated in terms of water saturation.) Experience proves that the points define a single, smooth curve, such as that shown on Figure 7. If the densities of the oil and water and the oil-water interfacial tension are known, use of equation (6) also permits showing in ordinates the curvature C of the interface and the height h of the sample above the free liquid level. This is possible, since P_c, C and h are directly proportional to one another.

Figure 7 shows that it takes a certain minimum capillary pressure P_D to start the desaturation process. This pressure P_D is that developed across the flattest interface that can exist on the sample surface in contact with the intruding non-wetting fluid. Thus P_D corresponds to the largest pore, or more exactly the largest pore entry, on that surface. Figure 7 also shows how the wetting fluid

saturation gradually decreases to its irreducible value, as the pressure is increased above P_D.

Interpretation of Capillary Pressure-Water Saturation Curve in Terms of Permeability, Pore Size and Pore Size Distribution

The $P_c - S_w$ curve actually defines the relationship between the curvature of the oil-water interfaces and the water saturation of the sample as a whole. Evidently, the greater the curvature at a given water saturation, the finer the pore size or, more exactly, the size of the pore entry must be. Thus it may be said that the *value* of the capillary pressure read on the $P_c - S_w$ curve for a given water saturation of the sample reflects the size of the pores in that sample which contain oil at that saturation. Since the pore size is a determinant of permeability, the $P_c - S_w$ curve may also be said to reflect the permeability distribution of the sample.

By the same token, the *shape* of a $P_c - S_w$ curve through the saturation range reflects the pore size distribution of the sample. Thus, in the case of Figure 7, the curve comprises first a low, very gently rising plateau extending all the way from 100 percent water saturation to near the irreducible value, then a narrow region where the slope increases rapidly, and finally a steep-sloped line quickly approaching the irreducible value. These characteristics indicate an overwhelming preponderance of large, well interconnected pore and a corresponding minute proportion of fine pores.

Generally speaking, for equivalent P_D and porosity, the larger the angle A between the extensions of the plateau and steep slope, the lower the permeability of the sample.

Fluid Distribution in Homogeneous Reservoirs

Let it be assumed that a reservoir under study is perfectly homogeneous in its macroscopic pore structure and pore size distribution. For short, it will be called a homogeneous reservoir Then, samples (cores or plugs) taken from it at different levels will all yield the same desaturation $P_c - S_w$ curve, such as that shown in plain line on Figure 8. This one curve in turn represents the variation of the water saturation with depth, that is, the reservoir fluid distribution, at least in the range of irreducible to moderately high water saturations. In the lower, high water saturation part of the reservoir, a contingent phenomenon usually complicates matters somewhat. Its occurrence is shown in the laboratory by allowing a sample undergoing desaturation to re-imbibe some wetting fluid, through reduction of the pressure differential. A $P_c - S_w$ imbibition curve, shown in dotted line on Figure 8, is obtained which departs from, and lies below, the desaturation curve, the two curves together forming a hysteresis loop.[4] A similar phenomenon is believed to have taken place in the lower part of most reservoirs,

[4] Actually, a family of imbibition curves and hysteresis loops is obtained, one curve and one loop for each starting point of the pressure reduction.

as the migrating oil and the displaced interstitial water traded places with each other.

Thus, the fluid distribution curve of a homogeneous reservoir is a composite curve, following the desaturation curve in the irreducible to moderately high water saturation range, and lying somewhere within a broad hysteresis loop in the high saturation range, as shown by the dashed line of Figure 8.

[The homogeneous reservoir represented by Figure 8 has an appreciable displacement pressure and attains its irreducible saturation only gradually, at high capillary pressures. These characteristics indicate two things: first, the reservoir

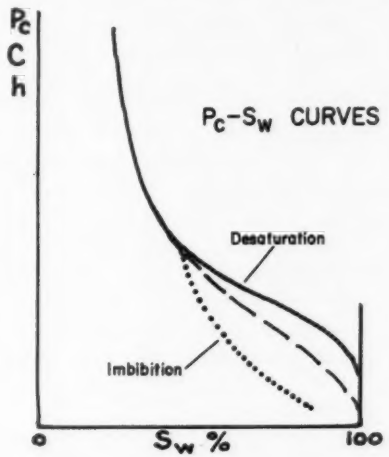


FIG. 8.

possesses a fine pore structure and a highly diversified pore size distribution (in contrast to the reservoir of Figure 7); second, and as a direct consequence, the reservoir has a fairly thick transition zone between the irreducible water zone that would produce clean oil and the high saturation zone that would produce water predominantly or exclusively. In Figure 8, gas of density d_g was also assumed to be present. Since $(d_w - d_g)$ is considerably greater than $(d_w - d_o)$, the gas-oil transition zone is always thinner than the oil-water transition zone, in a homogeneous reservoir.]

Coming back to generalities, two important remarks need still be made:

A. The displacement pressure P_D represents the minimum capillary pressure that the oil mass migrating into the reservoir space had to exert to enter the pore or interstice that is at once the largest and the lowest present on the lower boundary surface of the reservoir. Therefore the "free liquid surface" or "zero capillarity level," from which the height h of equation (6) is counted, is located below that particular pore.

B. The $P_c - S_w$ curve for a given homogeneous reservoir would allow immediate quantitative determinations of the water saturation at different heights, were it not for two facts:

1. Neither P_c nor C can be determined in situ;

2. The elevation of the free water surface, hence the height h of a level studied above that surface, cannot be determined from the curve.

If, however, one water saturation at a particular level is known through some other means (core cut with oil, well log analysis), the $P_c - S_w$ curve automatically becomes calibrated in height units, ready for water saturation determinations at other levels.

In any case, and without any outside assistance, the $P_c - S_w$ curve does give the irreducible water saturation of the reservoir.

Fluid Distribution and Fluid Contacts in Heterogeneous Reservoirs

Reservoirs are never perfectly homogeneous in their macroscopic pore size distribution. Even $P_c - S_w$ curves obtained in clean sandstone reservoirs exhibit slight variations from sample to sample.

In carbonate reservoirs, the basic laws governing the distribution, and the production, of fluids are the same as in sandstone reservoirs, but conditions are much more varied and complex, with consequences which may now be simply stated (assuming only oil and water to be present, and assuming constant densities, interfacial tensions and contact angle throughout the reservoir):

1. The capillary pressure is constant in any given horizontal plane, just as in a homogeneous reservoir.

2. To each such plane correspond a mean curvature C and a mean diameter D which an oil-water meniscus will take, again as in a homogeneous reservoir. But since C also determines the water saturation in a pore of given entry size, and since the pore structure and pore size distribution vary from point to point in the plane, the water saturation will likewise vary from point to point. Roughly all pores with entrance diameters larger than D will have admitted some oil, and all others will not. Thus in the same horizontal plane, areas may be found where the pores are very small and the water saturation extremely high, up to 100 percent, while in other areas larger pores hold the oil saturation in keeping with their size and elevation.

3. Thus, it is quite possible to find oil both above and below a water-bearing ledge or lens. One therefore runs the risk of not exposing the entire productive section by stopping drilling operations too soon. Figure 9 shows the log run in an Arbuckle dolomite in Kansas. The analysis of this log revealed the presence of a commercial oil accumulation below the fairly dense wedge zone at W on the figure, well below the subsea level previously recognized as the "water table" in the field.

4. The so-called "water table" or "water level," that is the level below which water would be produced predominantly or exclusively, should not be expected

to be a horizontal plane (quite aside from any possibility of hydrodynamic entrapment). The term "oil-water contact" is certainly far more appropriate. A log example of a water contact that changed 15 ft between two offset wells penetrating the same reservoir at approximately the same subsea datum due to a change of pore size and pore structure, will be shown later in Figure 19.

5. In fissures or fractures, the fluid distribution depends upon the width of the fissures or fractures, among other things. Quite generally, fissures and frac-

FIG. 9. Arbuckle Kansas.

tures are wide enough to contain only oil (except for molecular films of water on the walls), and constitute major avenues for its production. The oil-water contact in a wide vertical fracture may have a curvature and a capillary pressure so near zero as to represent the free water level. Such a contact thus is actually below the oil-water contact surface for the non-fractured portions of the reservoir.

IC. PROPERTIES BEST SUITED AND TECHNIQUES AVAILABLE FOR THE VOLUMETRIC EVALUATION OF A CARBONATE RESERVOIR. USE OF ϕ-S_W CURVES

This section has for its purpose to show which of the four properties, pore size distribution, total porosity ϕ, water saturation S_w and permeability K, are the most useful and diagnostic in the volumetric evaluation of a carbonate reservoir of given pore structure, and especially, how they are used.

Techniques Available

Before anything else, it is advisable to enumerate at once the techniques by which the four properties can be determined.

The pore size distribution can be rigorously determined only through capillary pressure tests made on samples of the pore structure studied. If such tests are not made, it must be estimated qualitatively through microscopic examination of the rotary cuttings or cores[5] and reference to previously correlated rock type data (see Archie's classification, Figure 12 of this paper).

Permeability determinations in the numbers needed in a carbonate reservoir statistical evaluation (see Part II) are available only through core analysis.

The total porosity can be determined either through core analysis or through the analysis of so-called porosity or ϕ logs of suitable design. The possibilities and limitations of such logs are discussed in Part III. As to core analysis, it must be noted that the total porosity and water saturation can be determined on the same sample only if the dry method for grain density determination is used and if the cores or plugs have not been subjected to capillary pressure tests by mercury injection. Thus, if capillary pressure tests are desired, it will be necessary to conduct the porosity determination and the capillary tests on two adjacent, but separate samples. This procedure, of course, is undesirable in heterogeneous rocks.

The water saturation can be determined either through core analysis or through the interpretation of so-called R_t or "true" resistivity logs designed to investigate the portion of a reservoir beyond the invaded annulus where mud filtrate invasion has disturbed the virgin fluid distribution. Again, the possibilities and limitations of such logs are discussed in Part III. As to core analysis, the procedure depends upon whether the cores were cut with water-base mud or oil-base mud. In the first case, only the residual water saturation can be obtained, unless the cores are submitted to capillary pressure tests, in which case the irreducible water saturation is also obtained. If the cores were cut with an oil-base mud, the water saturation may be measured directly on the cores. This is due to the fact that the interstitial water in such cores is not displaced by the oil-base mud, (except near the oil-water contact where the relative permeabilities to oil and water are nearly equal, or in depleted water drive reservoirs).

Statistical Interdependence of Four Properties

The four properties are not independent of one another. Actual measurements and reasoning both indicate that the water saturation and the permeability are statistically related to the porosity, which itself is determined by the pore structure and pore size distribution of the volume considered.[6] Generally, it is ob-

[5] The microscope can "see" no smaller pores than those penetrated by mercury at about 5-atms. pressure.

[6] Hence the introduction of the dimensionless, so-called J-function proposed by Leverett:

$$J(S_w) = (P_c/T \cos\theta)(K/\phi)^{0.5}.$$

served that as the porosity of a given type of rock increases, the permeability increases in a more or less logarithmic fashion and the water saturation decreases in a regular manner.

Suitability of Four Properties for Statistical Study

Proceeding now to the heart of the matter, the four properties are not equally suitable for a volumetric evaluation, and especially for their interpretation in terms of initial production and commercial value. In sandstone reservoirs, permeability and water saturation are very often used as the major criteria by which productive pay is separated from non-productive rock. In a carbonate reservoir of given pore structure, the three volumetric elements of greatest use are the pore size distribution, the total porosity and the water saturation. Permeability is rarely used for separating ray from non-pay carbonate rock because of its innate propensity to vary within extraordinarily wide limits.

Statistical Relationships between Porosity and Water Saturation. Their Characteristics and Uses.

Porosity and water saturation owe their diagnostic value in carbonate reservoirs to the existence of a definite statistical relationship between them, in a rock of given pore structure and pore size distribution. Furthermore, the graphical representation of that relationship provides a most simple and convenient means for statistically handling any number of capillary pressure, porosity and water saturation data, for separating productive pay from non-pay rock, and for estimating the average water saturation in the pore structure studied.

These statements may be made clear by considering two typical pore structures exhibiting such relationships.

The first example corresponds to a carbonate reservoir made up of a dense, essentially uniform, water-bearing matrix with very little porosity and negligible permeability, but endowed with secondary porosity due to solution, the solution voids ranging from pin-point to vuggy. Whatever oil this reservoir contains will be located in these voids and whatever oil is recovered will depend upon the number and sizes of the voids and their degree of interconnection. (Reef reservoirs are often of this type.)

Experience shows that a cartesian plot of the ϕ and S_w values determined in proximate intervals in such a reservoir, define a single curve of the form $\phi S_w = \text{Constant}$.[7] Figure 10, reproduced from Archie, shows two such curves for the upper and lower part, respectively, of a San Andres (Permian) limestone reservoir of West Texas. The porosities and water saturations were measured on cores cut with an oil-base mud, in a program involving five wells.

[7] The trend may be explained semi-quantitatively. In a reservoir of this type, the water saturation in the evenly textured, fine matrix is practically constant. Thus an increase in porosity also theoretically entails substitution of oil-containing voids for water-containing pores, hence, decrease in bulk interstitital water. The decrease is most marked and most readily observable when the bulk water saturation is high.

Figure 10 illustrates the use of $\phi - S_w$ curves for separating productive pay from non-pay rock. The water saturation is seen to increase rapidly when the porosity falls below about 3 percent for the upper part of the reservoir, and 4 percent for the lower part. Upper intervals having less than 3 percent porosity and lower intervals with less than 4 percent porosity may be expected to produce

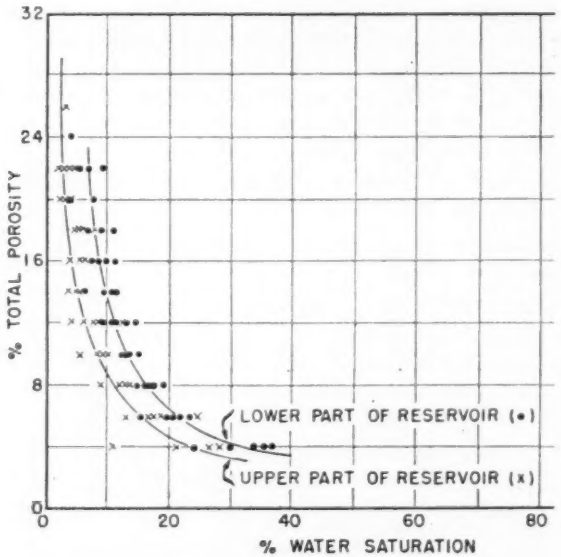


FIG. 10. (After Archie.)

water predominantly. Conversely, all porous-permeable intervals having greater porosities than these minimum or "cut-off" porosities may be considered as pay.

It should be noted that the value of the minimum or cut-off porosity increases with depth. That is, clean oil production can be obtained from lower porosity rock high in a reservoir than at lower levels. This is a general rule confirmed by capillary pressure tests, which show that for a given porosity, the higher the capillary pressure applied (the higher the elevation above the free water level), the lower the resulting water saturation.[8]

A second example of pore structure for which $\phi - S_w$ relationships may be

[8] If the reservoir is relatively thin, a single $\phi - S_w$ curve for the median elevation of the reservoir will generally suffice.

usefully established in a carbonate, or for that matter a sandstone reservoir, is the intergranular type. In such a pore structure a mere change of pore size will not affect the porosity (since the relative proportions of solid matter and void space remain unchanged), but will affect the water saturation and permeability, as shown in Section IB. Thus, it is possible for granular reservoir volumes to have

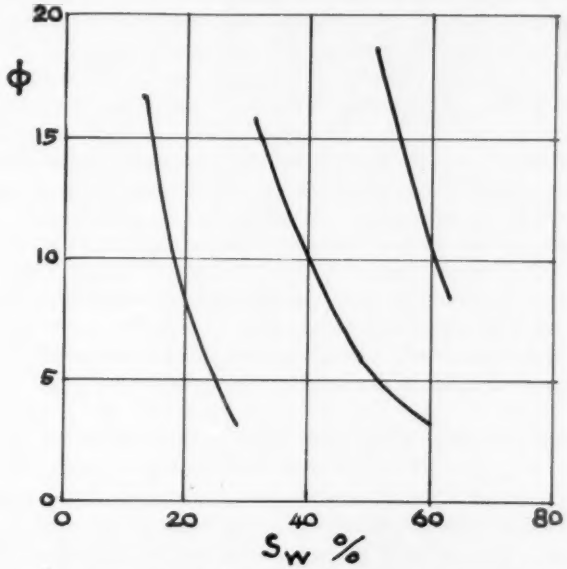


FIG. 11.

identical porosities but different pore sizes and pore size distributions, and very different water saturations. Figure 11 illustrates this point.

In granular reservoirs therefore, extreme attention must be paid to the pore size distribution as well as to the accuracy of the porosity and water saturation determinations by, say, log analysis. Fortunately, as will be shown in Part III, log analysis is normally at its best in these reservoirs. For one thing, they usually are fairly well stratified, an attribute which will be shown to favor their accurate evaluation through logs. For another thing, the resistivity of a rock volume varies a good deal more rapidly than does the water saturation, when the pore size distribution changes. Thus comparison of the resistivity log and the log used for porosity determinations can often diagnose changes in pore size in granular

reservoirs. This procedure is particularly useful in very fine pore structures, in which variations of pore size are difficult to detect with the ordinary power of magnification used in the microscopic examination.

There are, of course, many reservoirs which are neither of the solution porosity type nor of the granular type just discussed. For instance, the changes in porosity may be due to one type of pore structure grading into another. If the transition is smooth and solely, or at least primarily, responsible for the porosity changes, a relationship $\phi - S_w$ can be developed. If, however, more than two types are involved, an unambiguous $\phi - S_w$ relationship usually cannot be developed. Again, the reason for these facts lies in the laws controlling the fluid distribution in a reservoir.

Reservoirs where several pore structures and pore size distributions are present but so variable and mixed as to defy separation from one another, clearly, should not be expected to yield definite, usable $\phi - S_w$ trends. Evaluation of such a reservoir must obviously rely to an unusual degree upon detailed lithological work and capillary pressure tests, in order to establish the types and characteristics of the pore structures present. Once the reservoir has been so investigated, and comprehensively logged also, in the first few wells, it may be evaluated in subsequent wells through the combination of detailed description of the rotary cuttings and detailed analysis of suitable well logs.

PART II. THE DUAL STATISTICAL APPROACH IN THE EVALUATION OF A CARBONATE RESERVOIR

The facts reviewed in Part I make a statistical approach practically mandatory in the evaluation of a carbonate reservoir, whatever the specific techniques used. Such an approach, used in each well drilled in the reservoir, is in fact doubly necessary , so to speak, since the pore structure and the diagnostic properties vary greatly, both vertically and radially, and yet for all intents and purposes can only be observed in the direction of the borehole. This is indeed a situation, if there ever was one, to which the sound procedures and the inherent logic of the statistical treatment of a conglomeration of variable data should be applied.

Obviously, whatever diagnostic data are assembled must be referred to, and therefore grouped under, the specific pore structure to which they pertain. The statistical evaluation will therefore involve two consecutive operations in each well drilled.

A. Precise, detailed identification and description of the pore structures successively encountered by the well, and of the depths at which they occur, from the top to the base of the reservoir.

B. For each pore structure thus identified and located, performance of the greatest practicable number of determinations of the diagnostic properties. If several techniques are used, this second operation is to be repeated with each, and the results carefully tagged by technique.

IIA. IDENTIFICATION AND DESCRIPTION OF THE PORE STRUCTURES ENCOUNTERED

The detailed, precise identification and description of the pore structures encountered in a well is made possible by painstaking microscopic and macroscopic examinations of the rotary cuttings or cores recovered from the reservoir. The visible pore size distribution and the matrix pore fraction should be estimated with extreme care, particularly if capillary pressure tests are not to be made, through microscopic examination and reference to a suitable rock texture and pore structure classification, such as that shown in Figure 12, to be discussed shortly. The geologist supervising the drilling of the well is always well advised to observe the rotary cuttings or core chips under different powers of magnification, and to use reticulation lines to help him estimate and report closely the various textures, grain sizes and pore sizes which he sees. Photographs taken at some suitable magnification power are also a definite help for imparting this type of information to others, and for preserving it for future reference. Needless to say, the depths of all intervals studied should be carefully checked.

A complete, detailed description of the lithology, matrix texture, pore structure and visible pore size distribution is mandatory in every well. This is true even though in wells drilled after the first few, the very magnitude of the numerical values obtained through the evaluation techniques used may often seem to suggest or even predicate the pore structure or the pore size distribution. These values quite possibly could also fit another pore structure or pore size distribution due to rock type changes, and result in an entirely different interpretation in terms of initial production and commercial value.

Evidently, the accurate description of the rocks and pore structure types encountered can be greatly aided through the use of a classification system emphasizing pore structure and so designed as to reduce as much as possible the "personal equation." Archie's classification, proposed in 1951 is of this type. It consists of two parts: texture of matrix and character of visible pore structure. Three types of matrix texture are recognized, Type I: compact crystalline, Type II: chalky, Type III: granular or sucrosic. For each type the visible pore size is separated in four classes A, B, C and D, the pore size increasing from A to D. Figure 12 reproduces Archie's criteria for his classification. It should be noted that such a classification lends itself to the description of rotary cuttings as well as cores. Figure 13, reproduced from Archie, shows typical capillary pressure-saturation curves for the three types.

Cores, if and when available where wanted, are obviously the object of both the desired description and the desired quantitative measurements. No possibility should exist therefore for mismatching the results of these measurements and the pore structures. The use of a core surface gamma-ray log is also helpful in matching the depths of the cores with the depths of the corresponding rocks in place, as read on well logs.

When only rotary cuttings are available, on the other hand, all precautions

CLASS (TEXTURE OF MATRIX)	APPEARANCE OF HAND SAMPLE	APPEARANCE OR LUSTER UNDER MICROSCOPE (ABOUT 10X)		CRYSTAL OR GRAIN SIZE (MM)		APPROXIMATE POROSITY (%)					
						TYPE A MATRIX (NOT VISIBLE 10X)	VISIBLE POROSITY (% OF CUTTING SURFACE) SIZE OF PORE - MM			TOTAL POROSITY (SUM OF MATRIX AND VISIBLE	
							-0.1 - MM TYPE B	0.1 - 2.0 MM TYPE C	2.0 MM TYPE D	A - B	A - C
		GENERAL	RANGE								
I COMPACT	CRYSTALLINE, HARD, DENSE, SHARP EDGES AND SMOOTH FACES ON BREAKING. RESINOUS	MATRIX MADE UP OF CRYSTALS TIGHTLY INTERLOCKING, ALLOWING NO VISIBLE PORE SPACE BETWEEN THE CRYSTALS, OFTEN PRODUCING "FEATHER-EDGE" APPEARANCE ON BREAKING DUE TO FRACTURING OF CLUSTERS OF CRYSTALS IN THIN FLAKES, PROBABLY ALONG CLEAVAGE PLANES.	RESINOUS	L°	0.4	2	E.G. 10%	E.G. 15%	***	12%	17%
			TO	M	0.2						
				F	0.1						
			VITREOUS**	VF	0.05	5	E.G. 10%	E.G. 15%		15%	20%
II CHALKY	DULL, EARTHY OR CHALKY APPEARING, HARD TO SOFT. CRYSTALLINE APPEARANCE ABSENT BECAUSE THE SMALL CRYSTALS ARE LESS TIGHTLY INTERLOCKED, THUS REFLECTING LIGHT IN DIFFERENT DIRECTIONS, OR MADE UP OF EXTREMELY FINE GRANULES OR SEA ORGANISMS. MAY BE SILICEOUS OR ARGILLACEOUS.	CRYSTALS, LESS EFFECTIVELY INTERLOCKING THAN ABOVE, JOINING AT DIFFERENT ANGLES. EXTREMELY FINE TEXTURE MAY STILL APPEAR "CHALKY" UNDER THIS POWER, BUT OTHERS MAY START APPEARING CRYSTALLINE. GRAIN SIZE FOR THIS TYPE IS LESS THAN ABOUT 0.05 MM. COARSER TEXTURES CLASSED AS TYPE III.	CHALKY**	VF	0.05-	15	E.G. 10%	E.G. 15%		25%	30%
III SUCROSIC	SANDY OR SUGARY APPEARING (SUCROSE).	CRYSTALS LESS EFFECTIVELY INTERLOCKED, FRACTURE GENERALLY ALONG INDIVIDUAL CRYSTAL FACES GIVING A ROUGH OR SANDY APPEARANCE GENERALLY, MORE SPACE BETWEEN CRYSTALS. OOLITE, PISOLITE AND OTHER GRANULAR TEXTURES ALSO FALL IN THIS CLASS.	FINELY SUCROSE	F	0.1	10	E.G. 10%	E.G. 15%		20%	25%
				M	0.2						
			COARSELY SUCROSE	L	0.4	5	E.G. 10%	E.G. 15%		15%	20%

°L LARGE (COARSE); M MEDIUM; F FINE; VF VERY FINE.

** IN CASES WHERE CUTTINGS ARE BETWEEN VITREOUS AND CHALKY IN APPEARANCE, DESIGNATE AS I-II OR II-I. SAMPLES ARE CONSIDERED IN THE VF GROUP WHEN THE GRAIN OR CRYSTAL SIZE IS DIFFICULT TO DISTINGUISH (12X - 18X). PUT IN F GROUP WHEN GRAINS ARE EASILY DISTINGUISHED.

*** WHEN PORES ARE GREATER THAN ABOUT 2.0 MM AND THEREFORE THE PORES OCCUR AT THE EDGE OF THE CUTTINGS (FOR EXAMPLE, SUB-CAVERNOUS PORES) AMOUNT OF SUCH POROSITY IS INDICATED BY THE % OF CUTTINGS IN AN INTERVAL SHOWING EVIDENCE OF LARGE PORES.

SYMBOLS

III F - B_{10} FINELY SUCROSE (THEREFORE, MATRIX POROSITY ABOUT 10%); VISIBLE POROSITY ABOUT 10%, TOTAL POROSITY ABOUT 20%.

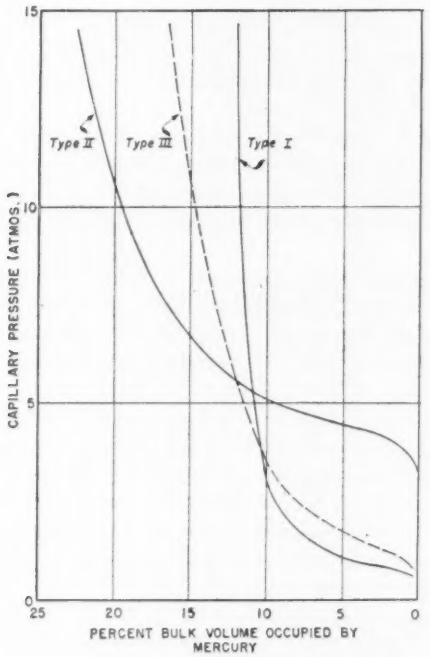
II - I VF-A CHALKY TO VITREOUS, VERY FINE TEXTURE (THEREFORE, MATRIX POROSITY ABOUT 6%), NO VISIBLE POROSITY, TOTAL POROSITY ABOUT 6%.

FIG. 12. Classification of carbonate rocks. (After Archie.)

should be taken to evaluate correctly the time elapsed during the ascent of the cuttings to the surface. Drilling time logs of any acceptable type and all pertinent data on the drilling mud properties are therefore an indispensable tool in the evaluation.

IIB. STATISTICAL PROPERTY DETERMINATIONS FOR EACH PORE STRUCTURE

In a given well, the scope of the statistical determinations made of the diagnostic properties (pore size distribution, total porosity and water saturation[9]) in



TYPICAL P_c-S_w CURVES FOR DIFFERENT CARBONATE RESERVOIR ROCKS

FIG. 13. (After Archie.)

each pore structure present, the validity of any evaluation based upon these determinations, and the cost of the entire evaluation endeavor, obviously depend on two groups of elements:

1. *The nature and aggregate thickness of the pore structure studied.*

At equal thickness not nearly so many valid or representative determinations are possible in a fractured or a cavernous reservoir as in a reservoir where the pore structure is intercrystalline or intergranular. Likewise, only a few ft of a given pore structure will not afford so broad a scope of statistical observations as many ft of it would.

---

[9] If cores are analyzed, the permeability is usually determined also and, if not too widely variable, may receive the statistical treatment.

2. The possibilities and limitations of the techniques used for determining the diagnostic properties.

Looking back, there are only two major classes of techniques that can give the type of volumetric evaluation wanted.

The first is diamond coring followed by core analysis, capillary pressure tests and other petrophysical determinations (see Section IIIA). This major technique is sometimes referred to as "direct," because a portion of the reservoir, however infinitesimal and possibly incomplete, is actually available for examination and measurements.

The other major class is well logging, often referred to as "indirect." As will be seen in Sections IIIC and IIID, well logs involve larger volumes than cores do.

The desired objective of either major technique can be stated simply enough: the technique should permit a number of individual determinations of the diagnostic properties selected, sufficient to establish the volumetric characteristics of the reservoir, through its entire height, on a sound statistical basis. By individual determination is meant the determination of all the diagnostic properties desired, limited to a rock volume within which they are essentially constant.

How to reach the objective however is not as simple as its statement. For one thing, and as already pointed out, there is the limited thickness of the reservoir. For another thing, each technique has possibilities and limitations of its own.

(a) First of all, attainment of the objective implies that the technique is able not only to recognize the constancy of the properties, but also to permit dividing the vertical extent of the reservoir in intervals or volumes, each with constant properties.

In theory cores of the reservoir, if recovered in full, afford the easiest way to accomplish both ends. In practice however, and particularly in poorly stratified carbonate rocks, boundaries between different pore structures and pore size distributions may be difficult to define, and it may be next to impossible to shape a plug or divide a full diameter core that will at once be large enough with respect to the pore size, yet small enough not to involve different pore structures. This difficulty has indeed already been recognized in the discussion of $\phi - S_w$ relationships.

As to well logs, they yield apparent readings of the quantities they measure, rather than true values. Discussion of this well-known fact belongs in Sections IIIB, IIIC and IIID. All that need be said here is that a log will recognize the existence of a constant property volume, and permit its separation from others above and below, only if each volume has certain minima vertical and radial dimensions (measured from the borehole) set by the log.

To sum up, the constancy of properties in any reservoir volume or interval is vouched for by the technique used.

(b) The second general observation regarding the attainment of the objective is that the technique used does not necessarily allow representative determinations of the diagnostic properties in each and every interval it has isolated. This point raises a number of questions, one of a general order applicable to both major

techniques, some specific to each technique. It is not the purpose of this paper to discuss any specific possibilities and limitations of core analysis determinations.[10] The one question applicable to both major techniques however must be mentioned.

Ideally, all the diagnostic determinations needed for the volumetric evaluation of a reservoir, a carbonate reservoir especially, should be made on the *same identical* plug or core or rock volume. In practice however core analysis does not permit this to be done except if the cores were cut with oil-base mud and if no capillary pressure tests are made. As to well logs, it will be seen in Section IIIC that the logs designed to reflect the porosity involve different, and usually smaller volumes, than those investigated by the saturation logs.

It should be noted that even if the same volumes were involved in the porosity and water saturation determinations, representative values of these properties are not always necessarily obtained.

In the case, for instance, of a plug or core taken from a vuggy reservoir, with some of the vugs exposed on the surface, the missing portions of these vugs will not be represented in the core analysis, which assumes that the fluid distribution in each partial vug is the same that would exist in the whole vug. For instance again, in a core containing a natural (not induced) fracture, there is no guarantee that the core containing this fracture, if measured, duplicates the exact condition it had at depth.

As to well logs, it will be seen in Sections IIIB, IIIC and IIID again that a log can yield an apparent value that can be corrected to "true" value only if the homogeneous volume analyzed has vertical and radial dimensions even larger than those required for its mere recognition and separation. This is indeed the reason why so-called conventional resistivity devices using non-focused currents are of very little use even in non-statistical evaluations of carbonate reservoirs.

In principle, and if one neglects matters of cost, time, and completeness of recovery, the analysis of cores, preferably cut with an oil-base mud, and capillary pressure tests allow the greatest number of statistical determinations. Also, as will be pointed out in Sections IIIA and IIIC, these direct methods serve to calibrate the responses of various logging devices in terms of porosity and water saturation. On the other hand, well logging techniques give continuous records of quantities measured in situ, which can be obtained rapidly and at relatively low cost and which when properly interpreted yield representative values of the diagnostic properties desired. Without going further into the matter, one therefore perceives that coring and logging will necessarily share the responsibility in the evaluation of a carbonate reservoir of any dimensions.

IIC. MECHANICS OF STATISTICAL VOLUMETRIC EVALUATION

The statistical evaluation of a carbonate reservoir requires systematic procedures for determining, reporting and handling the large number of desired data.

[10] For these, the reader is referred to API RP 40, September 1959.

This section briefly describes a system through which any number of porosity and water saturation values can be speedily and conveniently handled through the construction of $\phi - S_w$ curves, and, when available, $P_c - S_w$ curves. The case of reservoir data obtained from cores cut with a water-base mud and subjected to core analysis and capillary pressure tests will be discussed first. The case of reservoir data obtained from cores cut with an oil-base mud or through log analysis will then be reviewed.

Construction of $\phi - S_w$ Curves and $P_c - S_w$ Curves through the Analysis of Cores Cut with a Water-base Mud, and Capillary Pressure Tests

In each well:

1. The reservoir is cored, preferably in its entirety, and the recovered cores preserved by appropriate means.
2. The recovered cores are examined microscopically and macroscopically.
3. On the basis of these examinations the various pore structures and rock types are segregated whenever possible, each portion of core being carefully marked for depth.
4. From the aggregate footage recovered in each rock type, portions of the full diameter cores are selected in sufficient number to provide a good statistical coverage of the entire range of desired properties. If the reservoir is thick, sampling every foot may be sufficient.
5. Adjacent plugs are taken from each core, one for the determinations of the residual hydrocarbon and water saturations, and of the total porosity, and another for the capillary pressure tests.
6. The residual hydrocarbon and water saturation, and the total porosity are determined on each plug selected to these ends.
7. The capillary characteristics of the other plug of each core are determined. The mercury injection method greatly speeds up these determinations and reduces their costs. Usually, only a few pressures are needed to define the capillary pressure-wetting fluid saturation relationship. The pressures at which the measurements are made should be the same for all the plugs, in order to simplify the statistical work involved in the next steps.
8. For each pore structure, the total range of porosities measured in step 5 is divided into suitable porosity "classes."
9. All cores or plugs whose porosity fall within the limits of a class, say 8.0 and 9.9 percent, are tabulated in that class. For each interval thus entered in the class, the depth, the actual porosity value measured, and the water saturations obtained at the different capillary pressures used, are tabulated on the line corresponding to the interval, each value in its proper column.
10. The porosity values of all the intervals entered in the porosity class are totalled. Likewise, the water saturations for each capillary pressure used are totalled. An average porosity value, and average water saturations for the different pressures, are then calculated.

11. The procedure outlined in steps 9 and 10 is repeated for each class of porosity.

12. The average porosity and water saturation values thus obtained for all the samples of the pore structure under study are then reported on one or both of two general statistical plots:

a. $P_c - S_w$ plot for the various class average porosities. This plot will have as many $P_c - S_w$ curves as there were porosity classes used.

b. $\phi - S_w$ plot for the various capillary pressures P_c used. This plot will have as many $\phi - S_w$ curves as there were constant capillary pressures used.

Construction of $\phi - S_w$ Curves through the Analysis of Cores Cut with an Oil-base Mud, or through the Analysis of Well Logs

If the cores were cut with an oil-base mud and capillary tests are not made, or if the porosity and water saturation values are derived through log analysis, the statistical work of steps 8 through 12 follows essentially the same routine as that outlined for cores cut with water-based muds, but there is only one water saturation to be reported for each interval studied, and no possibility of constructing a $P_c - S_w$ plot. However, as indicated in the discussion of Figure 10, in Section IC, if the reservoir is thick enough, it is generally advisable to group the intervals not only according to their porosity class but also within appropriately selected depth limits. $\phi - S_w$ curves for the median points between consecutive depth limits may then be constructed. If depths have no apparent effect on the $\phi - S_w$ plots, the reservoir may be either a depletion type reservoir, or remotely situated from water.

PART III. VOLUMETRIC EVALUATION OF CARBONATE RESERVOIRS THROUGH WELL LOGS

Under proper conditions, well logs permit measuring certain properties of rocks such as specific resistivity, velocity, radioactivity, response to bombardment by fast neutrons or by gamma rays, etc.; or phenomena such as the potentials occurring at contact surfaces between a shale and a pervious rock and between these and a mud column. Volumetric evaluation through logs is possible thanks to the existence of a number of more or less well-defined relationships among these petrophysical properties or phenomena on the one hand, and porosity, water saturation, permeability on the other. Hence the statement often heard that well logging is an "indirect" method of obtaining reservoir data.

This part of the paper has for its purpose to discuss briefly the few relationships and logs which are most frequently used in carbonate reservoirs today. The relationships will be stated only in the case of reservoirs essentially devoid of shaly or colloidal material, or for short, "clean" reservoirs. The point is that whenever a log can be used and interpreted in a clean reservoir, it can also be used and interpreted in a shaly reservoir if the clean reservoir relationship can be written in a more general form including shaly reservoirs.

As well known, the relationships which express the singular dependence of the resistivity of a formation upon the fluid content of the latter are the cornerstone of formation evaluation through logs today. Their scope and validity of application in carbonate reservoirs must therefore be defined first.

IIIA. RESISTIVITY-FLUID CONTENT RELATIONSHIPS IN CLEAN CARBONATE RESERVOIRS

Origin and Statement of Relationships

The relationships to which the present discussion is limited apply to any clean porous-permeable reservoir volume which is preferentially water-wet and which possesses a homogeneous pore structure of the intergranular type. They were discovered through measurements made on sand and sandstone core plugs, and first formally proposed by Archie in 1941. They read:

$$R_o = FR_w \quad \text{giving} \quad F = R_o/R_w, \tag{7}$$

$$S_w^n = FR_w/R_t = R_o/R_t = 1/I, \tag{8}$$

$$F = 1/\phi^m, \tag{9}$$

where:

ϕ is the total porosity of the volume considered,

S_w is the water saturation of the volume, expressed as a fraction of ϕ;

R_o is the specific resistivity of the volume completely saturated with an interstitial water of resistivity R_w ($S_w = 1$ or 100 percent);

F, the ratio R_o/R_w, is the formation resistivity factor, found by Archie to be a constant characteristic of the pore structure of the clean rock volume, independent of the resistivity R_w of the saturating water;

R_t is the specific resistivity of the volume when the water saturation therein is S_w;

$I = R_t/R_o = S_w^{-n}$ is the "resistivity index";

n and m are the "saturation exponent" and the "formation resistivity factor exponent," respectively, of the volume considered. Archie's original determinations, and innumerable others since, have shown that m and n vary according to the origin and pore structure of the sands and sandstones measured.

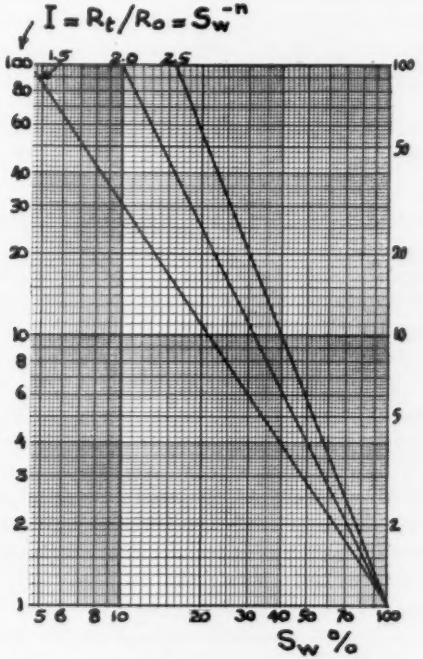
Figure 14 graphically represents equation (8) on log log paper, with the resistivity indices $I = R_t/R_o = R_t/FR_w$ reported in ordinates and the water saturations S_w in abscissae. The result is a straight line of slope n. Three n values are shown, 1.5, 2.0 and 2.5, to be discussed later. Figure 14 shows that the resistivity rock is very sensitive to a variation in water saturation. Thus for a rock with a saturation exponent $n = 2.0$, I increases four times when the water saturation is decreased by half (for $S_w = 40\%$, $I = 6.3$; for $S_w = 20$, $I = 25$). This is the reason for the statement made in Section IC that the resistivity of a rock is more sensitive to a change in pore size distribution than is the water saturation.

Combining equations (8) and (9) gives equation (10):

$$S_w^n = R_w/\phi^m R_t. \tag{10}$$

Equations (8) and (10) show that the water saturation of a homogeneous granular reservoir volume of given exponents m and n and given interstitial water resistivity R_w can be calculated if the resistivity R_t and either the formation resistivity factor F or the porosity ϕ of the volume can be determined. These are precisely the respective functions of suitable so-called R_t and $F-\phi$ logs, to be discussed shortly.

Archie and others eventually extended their statistical work to water-wet carbonate cores, preferably full diameter cores. Not unexpectedly, this yielded log log $I-S_w$ and $\phi-F$ plots, for each pore structure, showing greater scatter than similar plots in sandstones. Nevertheless, straight-lined $I-S_w$ and $\phi-F$ trends unmistakably appeared as reasonable averages in many cases, with slopes



I – S_W RELATIONSHIP FOR THREE VALUES OF SATURATION EXPONENT

FIG. 14.

n and m sometimes close to, sometimes markedly different from, those observed in sandstones.

Basically, equations (7) through (10) may be said to apply to Types I, II and III carbonate rocks, with or without solution porosity, provided that when solution porosity is present, the solution voids be not too large and be reasonably well interconnected. These are admittedly rather vague terms. A practical limit for the size of vugs would be in the $\frac{3}{8}$-inch to $\frac{1}{2}$-inch range.

Equations (7) through (10) also seem applicable or at least useful in highly fissured carbonates of all three types where numerous criss-crossing fissures divide the rock matrix in a large number of small pieces.

On the other hand, carbonate reservoirs of Types I or II which owe their productive capacity to widely scattered fractures or very large voids of secondary origin cannot be evaluated directly through the equations, although the individual matrix blocks between fractures or voids can. This is hardly surprising, if one recalls the origin of the equations. The evaluation of such reservoirs is a subject largely beyond the scope of this paper (see Section IIIC).

In brief, it may be said that equations (7) through (10) apply to any carbonate rock volume the pore structure of which, viewed on a fairly large macroscopic scale, assumes the highly and fairly evenly developed character of intergranular pore structures.

Significance and Values of Formation Resistivity Factor Exponent and Saturation Exponent

Two general statements need be made regarding the experimentally derived exponents m and n:

1. The first statement concerns the determination of these exponents. The determination of m requires complete cleaning and drying of each core plug, followed by thorough, repeated flushing of the plug with the water selected for the experiment, until complete stabilization of the ratio R_o/R_w is obtained. This second operation can be very long and tedious. The total porosity of the core plug must also be measured. As to n, it is determined in the course of either dynamic or restored-state capillary pressure tests and simultaneous resistivity measurements. Such determinations again can take a considerable time, particularly if the restored-state method is used. (Presumably it best duplicates reservoir conditions.) The time and expense involved in determining the two exponents partly explain why such determinations are rarely made, and why, when made, they are often kept confidential.

2. The second statement regards the significance of the two exponents. Both reflect the influence of pore structure on the electrical conductivity of a porous-permeable rock, m alone when the rock is 100 percent water-bearing, m and n both when the water saturation is not 100 percent. Happily simple exponents though they be, they are in fact the two agents which permit the application of such general relationships as equations (7), (8), (9) and (10) to a great variety

of pore structures. It is also possible to foresee that the more lengthy and tortuous the interconnections of the pore space of a rock (the greater its "tortuosity"), and the fewer these interconnections (the more cemented the rock), the more resistance that rock will oppose to the flow of an electric current, (or indeed to hydraulic fluid flow), and the greater the formation factor F of that rock should be.

Formation Resistivity Factor Exponent and Saturation Exponent in Sandstones

Archie, in his very careful pioneering work, found m to vary between values of 1.3 for unconsolidated sands and 1.8 to 2.0 for consolidated sandstones. This last range is used for most sandstones in practice, when using Archie's relationship $F=1/\phi^m$. Searchers following Archie proposed covering the same portion of the sandstone spectrum through the use of a statistical relationship of the type:

$$F = a/\phi^M, \tag{9'}$$

where a and M are constant. The most famous examples of such constant M relationships are the Humble formula in which $a=0.62$ and $M=2.15$ and the Wyllie formula in which $a=0.75$ and $M=2.0$. Figure 15 graphically represents the Archie, Humble and Wyllie relationships on log log paper, on which they appear as straight lines, each with a slope equal to the value of m or M involved, as the case may be. Archie's lines all pass through the point of co-ordinates $\phi=100$ percent, $F=1$. It is seen that Archie's lines for $m=1.8$ and $m=2.0$ and the Humble and Wyllie lines essentially yield the same ϕ range for a given F value or conversely the same F range for a given ϕ value, for a fairly wide range of porosities.

As to the saturation exponent n, it has been found to depend upon the technique used, whether static or dynamic, for varying the saturation of each core plug, as well as on whether the saturations are measured in a desaturation or an imbibition process. A great deal has been written on these subjects, about the wide limits found for n in the laboratory, and about its importance in log analysis. Extreme values in dynamic tests of 1.41 and 2.55 have been quoted for water-wet sandstones by various observers, the higher figure corresponding to synthetic cores. Much wider ranges however can be found in the literature, both for water-wet and oil-wet cores. Cutting through the maze of data, and making the reasonable assumption that n values obtained by static restored-state desaturation are closer to actual conditions in a reservoir, it seems that values in the 1.8–2.0 range give the best results in clean sands and sandstones.

Formation Resistivity Factor Exponent and Saturation Exponent in Cabornate Rocks

A great many determinations of m have been made over the years on cores from various carbonate reservoirs throughout the world. With very few exceptions however, the results are not available in print. From the scant evidence available, it appears certain that the exponent m can and does vary in carbonate

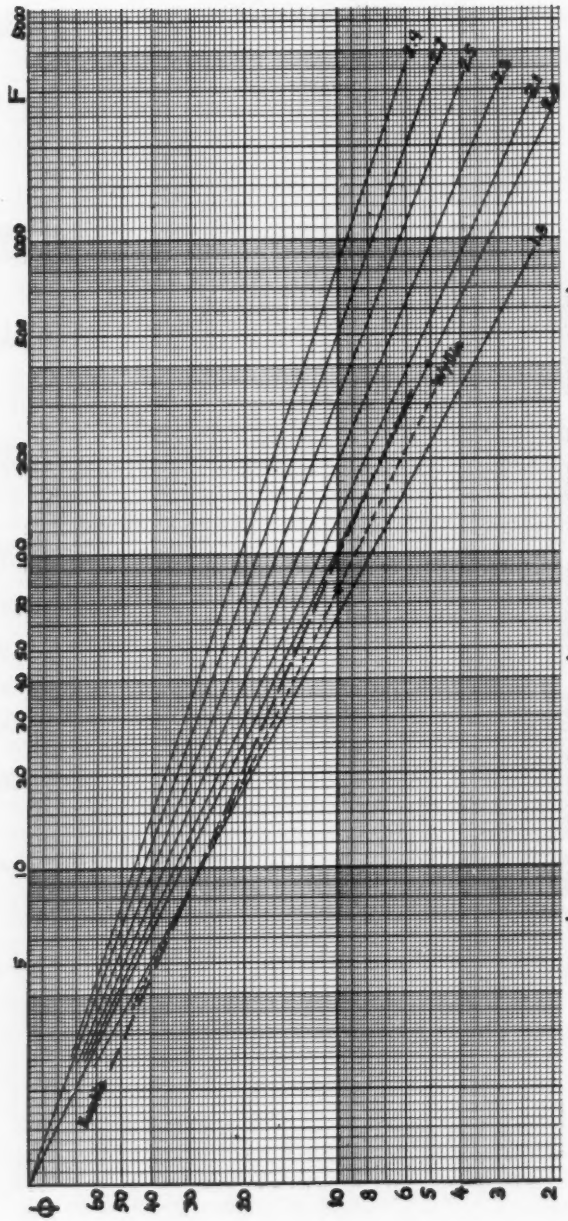


FIG. 15.

rocks within a range which is a good deal wider than, and different from, that found in sandstones.

Formation resistivity factor exponent ranges that appear to apply in the majority of cases are: 1.8 to 2.0 for pure crystalline Type I and pure granular Type III carbonates; 1.7–1.9 for pure chalky Type II rocks; 2.1–2.6 in carbonates of any type, when solution voids are present, the lower figure applying mostly to pin-point to small vugs, the higher figure to large vugs. The exponent m may be even higher than 2.6; a value of 2.9 has been quoted for some oolicastic pore structures. The lines corresponding to m values of 2.1, 2.3, 2.5, 2.7 and 2.9 are shown on Figure 15.

As to the saturation exponent n, again little information seems available. The exponent is highly variable, for the same reasons found at work in sandstones. In practice extreme limits of 1.5 and 2.2 are most plausible, the lower value corresponding to reservoirs with large vugs or solution voids, the higher values corresponding to fine crystalline, dense rocks, and the range 1.8–2.0 applying to most granular types.

Examples Showing Influence of m and n on Results of Log Analysis

It is important to realize that errors made in the selection of the exponents m and n may more or less vitiate the effectiveness and accuracy of an otherwise expert log analysis. Two simple examples will prove the point.

In the first example it is desired to evaluate a I–IIID rock interval having a true resistivity $R_t = 100$ ohms m^2/m and an interstitial water of resistivity $R_w = 0.1$ ohm m^2/m. The saturation exponent $n = 1.8$, and the correct value of the formation resistivity factor exponent is $m = 2.4$. What would be the result of evaluating this interval with the value $m = 2.0$? Two cases must be considered:

(1) The porosity is determined through a focused microresistivity log (microlaterolog or $F_o - R_{xo}$ log, or the newer proximity log).[11] Such a log yields the resistivity R_{xo} of the reservoir annulus flushed by the mud filtrate, which in turn yields the formation resistivity factor F. Let it be supposed that the formation resistivity factor thus determined is $F = 100$. Equation (8) yields the water saturation $S_w = 28$ percent, independent of m, but according to equation (9), or Figure 15, the porosity is only 10.0 percent if the incorrect value $m = 2.0$ is used, instead of 14.6 percent for $m = 2.4$. Thus, the $\phi - S_w$ relationship for this and other I–IIID intervals present in the reservoir is affected, their minimum or cut-off porosity will be set too low, and a faulty completion may ensue.

(2) The porosity is determined through an acoustic log, or a neutron log, or a gamma-gamma log (density log).[12] The interpretation of these logs yields the porosity, rather than the formation factor. Let it be assumed that one of these logs yields a porosity of 14.6 percent in the interval studied. The corresponding formation factor will be 100 if the correct $m = 2.4$ value is used, but only 47 if

[11] For a fuller discussion of these logs, and their interpretation, see Section IIIC.

[12] For a fuller discussion of these logs, and their interpretation, see Section IIIC.

$m = 2.0$ is used. Entering the two F values in equation (8) yields water saturations $S_w = 28$ percent (correct) and $S_w = 18$ percent (incorrect), respectively. Thus, use of the faulty m value in this interval and in all other I–IIID intervals results in an optimistic evaluation, an unrepresentative $\phi - S_w$ relationship, and a possibly faulty completion.

Consideration of Figure 14 shows the effect of an error on the saturation exponent n. An interval that calculates 30 percent water saturation for $n = 2.0$ has a water saturation of only 20 percent if the correct value of n is 1.5. Besides this major effect, an error on n also affects the porosity determinations made through focused microresistivity logs.

Practical Conclusions Regarding the Exponents m and n

The errors assumed on m and n in the two examples above were purposely made rather extreme for the sake of emphasizing three practical conclusions:

(a) Regardless of the techniques used, both exponents affect the evaluation of a carbonate reservoir through log analysis to a significant degree.

(b) For the most reliable evaluation of a new reservoir, the ranges of these exponents in the various pore structures encountered should be ascertained on a statistical basis, in one or more key wells.

1. Taking the formation resistivity factor exponent first, it should ideally be determined on cores. If this is not possible, one or more of three general methods may be used: (a) confrontation of core porosities and formation factors derived from focused microresistivity logs; (b) confrontation of formation factors from microresistivity logs and porosities derived from an acoustic log, or a neutron log or a density log; (c) matching the true resistivity of known 100 percent water-bearing intervals with their porosities, as determined by an acoustic log, or a neutron log or a density log. Methods (a), (b) and (c) cannot be expected to give as definite results as laboratory measurements, because, as will be recalled in Section IIIC, the interpretation of $F - \phi$ logs requires the making of one or more assumptions. Method (c) is satisfactory if the R_t log can be corrected exactly for the effect of mud filtrate invasion, if the intervals used are truly 100 percent water-bearing and have the same pore structures and the same rock types as those found in the reservoir to be studied, and if the resistivities of their interstitial waters are accurately known. (See Sections IIIA and IIIC.)

If the overall evaluation program does not include any of the above alternatives, the selection of probable m ranges for the various type rocks encountered will have to be made on the basis of the microscopic and macroscopic examination of the rotary cuttings, and of whatever experience with similar rocks is available in the area.

In practice, with due regard for all the information that is available at the time of logging, it is usually permissible to narrow the m range for a given pore structure to within ± 0.1 of a median value (e.g. 2.0–2.2).

2. The saturation exponent can be determined only through simultaneous

resistivity measurements and capillary pressure tests made on cores, preferably by the static restored-state method. If such determinations are not made, reliance must be placed upon the lithological description, or upon the evidence provided by drill stem tests, formation tests, or production tests. (An intergranular limestone flowing clean, gassy oil on a drill stem test can hardly have a water saturation in the 50 to 60 percent range.)

(c) Generally, the evaluation of each pore structure should be conducted with ranges rather than single values of the exponents m and n. Such a practice not only is realistic, but also helps the log analyst keep an open mind until his "raw" determinations in all the intervals that can be analyzed are completed and ready for his final appraisal of their statistical significance and $\phi - S_w$ trend.

Influence of $R_t - \phi - S_w$ Relationships on Minimum Logging Program for Reservoir Evaluation. Two General Requirements

Equations (7) through (10) point to the measurement of the specific or true resistivity R_t of rocks as another means for determining their water saturation S_w. This is indeed a most convenient means since rock resistivities can be logged continuously, rapidly, at relatively low cost with the rocks in place, wherever the latter are traversed by open boreholes.

The same equations also dictate certain basic requirements that a logging program suitable for reservoir evaluation purposes must meet. Two of these requirements may now be stated. A third requirement, based partly on the same relationships, partly on general considerations on log responses, cannot be stated until the latter have been discussed in Section IIIB.

First Requirement: Necessity for Independent R_t and F-ϕ Logs

Besides the S.P. log or the natural radioactivity or gamma-ray log, which is necessary for the lithological differentiation of rocks, a logging program for reservoir evaluation must comprise separate, independent R_t and $F - \phi$ logs.

The reason for this requirement is obvious, if R_t is put in evidence in equations (8) and (10), thus:

$$R_t = FR_w/S_w^n = R_w/\phi^m S_w^n. \tag{11}$$

It is seen that the reading of a R_t log in a given volume can be interpreted in terms of water saturation only if the formation factor F or the porosity ϕ of the volume is known by some other means, namely, either a core analysis or a $F - \phi$ log.[13]

[13] An apparent contradiction of this first requirement is the so-called "Rocky Mountain method," in which a group of two or more conventional (non-focused) resistivity devices of different spacings yields both R_t and the resistivity R_i of the zone invaded by the mud filtrate, and where S_w is determined first, without knowledge of either F or ϕ. However, the contradiction is only apparent: the method is actually predicated on two assumptions: the first, peculiar to the method, concerns the relationship existing between the water saturations in the invaded zone and the virgin reservoir; the second, indeed common to all logging methods, assumes that F and ϕ preserve the same values in the invaded zone and in the virgin reservoir. The method proved exceedingly useful in thick Rocky Mountain sandstones before the advent of modern focused F-ϕ logs.

The only case where the R_t log alone suffices is that of a formation known or assumed to be 100 percent water-bearing. (The assumption may be tantamount to a verdict without trial!) In that case, of course, a R_t log will yield a resistivity $R_o = FR_w$, according to equation (7). If R_w is known, F can be calculated: $F = F_o/R_w$, and the evaluation, based on a prejudgment, is effectively terminated.

Second Requirement: Necessity for Accurate Knowledge of R_w

The relationships show that the water saturations derived from a R_t log cannot be any better than the R_w values used.[14] The resistivity R_w of the reservoir interstitial water must therefore be known accurately. This requirement of long standing is acknowledged again here for two main reasons:

(a) Water salinities and resistivities in a carbonate reservoir of given age are prone to vary appreciably over short distances, a few miles at most, and should never be taken for granted;

(b) When R_w is determined through the S.P. log, the exact formula:

$$E_c = KT \log a_w/a_{mf} \tag{12}$$

should be used rather than the old formula:

$$E_c = KT \log R_{mf}/R_w. \tag{13}$$

In the above equations, E_c is the electrochemical component of the static S.P. log deflection observed in the porous-permeable formation under study, K is an electrochemical constant dependent upon the formation and surrounding shale beds, T is the absolute temperature of the level studied, a_w and a_{mf} are the activities of the interstitial water and the mud filtrate, respectively, and R_{mf} is the resistivity of the mud filtrate.[15]

Equation (12) should be used in preference to equation (13) because in many cases either the mud filtrate or the interstitial waters contain large concentrations of calcium and magnesium salts.

R_w determinations through the S.P. log can be made as soon as that log has been run, which is an advantage in a wildcat well or when the reservoir under study does not produce any water. It is most reliable when the ratio a_w/a_{mf} or its approximate equivalent R_{mf}/R_w is appreciably larger or appreciably smaller than unity, but preferably not in excess of 5 or less than $\frac{1}{5}$.

Other well-known and on the whole more certain methods to determine R_w, when feasible, are its direct measurement on a sample of water recovered either

[14] A reservoir volume for which $R_t = 90$ ohms m^2/m, $F = 100$, and $n = 2.0$, would have a water saturation equal to 24 percent, or 33 percent, or 41 percent, according to whether the interstitial water resistivity R_w is 0.05, or 0.1 or 0.15 ohms m^2/m (use Figure 14 with R_t/R_o values of 18, 9 and 6, respectively).

[15] The other component of the static S.P. is the streaming or electrofiltration component E_f. Hill and Anderson in particular suggest that E_f is of sufficient magnitude in the majority of cases to be taken into account when determining E_c.

through a drill stem test or in actual production, or calculation from the chemical analysis of such a sample.

The importance of preserving samples of waters recovered on drill stem tests can never be stressed too much in carbonate rocks. In a well drilled with a water-base mud, when water is recovered in a drill stem test, several samples should be taken along the height of the water column, and their positions carefully identified. On arrival at the well, the logging engineer may then measure the resistivities of these samples and of the mud filtrate. Through this procedure, mud filtrate contamination can be estimated and a satisfactory approximation of R_w obtained, in many cases.

IIIB. GENERALITIES ON WELL LOG RESPONSES AND THEIR SUITABILITY IN A STATISTICAL EVALUATION

It is fortunate indeed that the fundamental resistivity-fluid content relationships were first established for sands and sandstones: these formations on the whole are far more tractable sediments than carbonate rocks, at least for the purpose of establishing petrophysical characteristics and trends.

On the other hand, most of the advances made in well logging techniques, particularly since World War II, have been directed, one is glad to say with marked success, at the once well nigh insurmountable challenge posed by complex lithological sequences and more generally by heterogeneous rocks, of which carbonate rocks are the outstanding examples.

The Complex Task of Logging Devices

The above statements should not be taken to mean that carbonate reservoirs alone present a challenge to well logging and log analysis techniques. This is not at all the case. Carbonate reservoirs do however strain the possibilities of these techniques far more often and to a greater degree than most sandstone reservoirs do.

The task of logging devices is demonstrably not a simple one, even in clean, homogeneous sandstone reservoirs. First of all, these devices are constrained to operate within the confines of a borehole. This fact alone imposes restrictions on their design, mode and flexibility of operation. Secondly, all logging techniques must somehow cope with or take into account the influence of that borehole on the logs. Thirdly, they are necessarily designed for the most common drilling method in use today, namely, rotary drilling with a water-base mud. Under normal conditions that mud or its filtrate is allowed to invade all pervious formations present, to some extent.

Spacings of Logging Devices

Theory and experience concur to show that, in order to overcome or circumvent the borehole and invasion effects and, sometimes, restrictions on their own design or that of their companion circuitry, logging devices must, among other things, be given sufficient effective lengths or "spacings." The only modern

exception to this statement is the S.P. electrode, which theoretically could be reduced to a point. The word "spacing" is used here as a generic term. For conventional (non-focused) resistivity and microresistivity logs, it is the distance between current and pick-up electrodes. For "laterologs-7" and microlaterologs, it is the distance between central electrode and monitoring electrodes or rings. For "laterologs-3" and guard logs, it is the thickness of the central electrode. For the induction log, it is the distance between transmitting and receiving coils. For gamma-ray or natural radioactivity logs, it is the detector length. For neutron-induced and gamma-induced logs, it is the distance from source to detector. For acoustic logs recorded with a one-receiver device, it is the distance from transmitter to receiver. For acoustic logs recorded with two-receiver devices, it is the distance from transmitter to first receiver. (The interval between the two receivers is called the "span.")

"Apparent" vs "True" Values

Theory and experience demonstrate that logs yield "apparent," rather than "true" values, of the petrophysical properties which they reflect. Whether or not the apparent values read off the logs can be corrected back to the true values depends upon the facts of each individual situation.

The gap between apparent and true values in a given homogeneous volume actually depends upon all of these elements: (a) the nature of the property being measured (resistivity, velocity, etc.); (b) the ratio of the property level studied to the levels obtaining in the adjacent volumes ("property contrast"); (c) the type (mode of operation) and (d) spacing of the device used to measure the property; (e) the thickness of the given volume possessing the true property value considered; (f) the size of the hole and (g) the nature and properties of the fluid filling it; (h) the position or "eccentricity" of the device with relation to the walls of the hole (very important for all modern $F-\phi$ logs); (i) the mechanism and extent of invasion by the mud and/or mud filtrate; (j) in the case of a nuclear log, the time constant and the recording speed selected for running the log.

Primarily because the spacings of practical devices have non-negligible dimensions, all logs mark the boundary from one true level of properties to another true level by "transition patterns" straddling the boundary, rather than by sharp, instant level changes at the boundary. Again, the shapes of transition patterns and the thicknesses over which they extend depend upon all the elements (a) through (j) previously cited.

It is also a fact of logging that certain property-device combinations yield "straight" transition patterns, that is, patterns whose entire trend essentially goes in the same direction as the property change at the boundary. This is essentially the case of all modern focused R_t logs and $F-\phi$ logs. However, one of the best $F-\phi$ logs available today, the two-receiver velocity or sonic log, yields transition patterns which may not follow the velocity changes, whenever the thicknesses of consecutive property levels are smaller than the span used. Such

odd patterns are called "geometrical effects." An example of this will be shown in Figure 19.

Figure 16 illustrates the above points for several modern focused logs.

Generally speaking, the following facts should be remembered when selecting apparent values from logs:

1. Apparent property values shown by transition patterns are most generally beyond correction. The one use of such patterns is to indicate where changes in property level occur.

2. Barring geometrical effects, apparent values suitable for possible correction and use in quantitative analysis appear in the form of peaks or plateaus towards the high property levels, depressions or valleys towards the low property levels.

3. For a device of given type and spacing, the property logged must maintain the same level over a minimum thickness before this level can make its existence known on the log. For modern focused R_t and $F-\phi$ logs without geometrical effects, that thickness has been reduced to a spacing or even slightly less.

4. Again for a device of given type and spacing, the property logged must maintain the same level over a certain thickness if the log is to yield a "representative point" or preferably a "representative segment" for that level, whose apparent value can be adequately corrected for thickness, mud column and invasion effects (by means of appropriate calculations or charts), resulting in a near-true value fit to be entered into the quantitative log analysis relationships. That thickness again is a complex function of the factors (a) through (j) previously

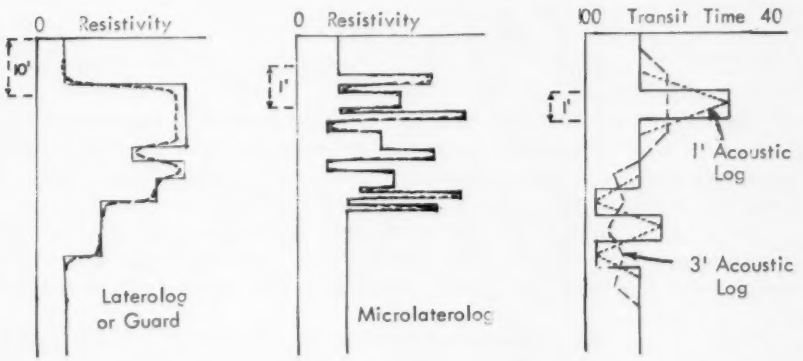


FIG. 16. Transition patterns and geometrical effects.

cited. For modern focused R_t and $F-\phi$ logs (other than nuclear logs), it varies from slightly over one spacing to two spacings or more. Nuclear $F-\phi$ logs require greater thicknesses. (See discussion of neutron-induced logs.)

Feasibility and Scope of Statistical Evaluation Through Well Logs

The conditions for the use of any log for purposes of statistical evaluation may now be summed up under three headings:

A. Not all points of a log by any means can be used in the study, statistical or otherwise, of a reservoir shown by this log.

B. Any reservoir volume that is thinner than the minimum thickness required by the $F-\phi$ log used cannot be evaluated in terms of formation resistivity factor and/or porosity. As a result, by virtue of equation (10), its water saturation cannot be determined either.

C. Any reservoir volume that is thinner than the minimum thickness required by the R_t log cannot be evaluated in terms of water saturation. If the R_t spacing is greater than the $F-\phi$ spacing, this volume quite possibly may be thick enough for porosity evaluation.

Requirement for Short R_t and $F-\phi$ Devices with Fine Vertical Resolution

In view of the conditions just stated the evaluation of a given reservoir will acquire its broadest and soundest statistical basis through the use of R_t and $F-\phi$ devices with the shortest spacings (or spans, in the case of two-receiver velocity logs) and the finest vertical resolution compatible with the performance of their assigned functions. Modern, focused logs were invented and are being continually improved partly in an effort to approach this goal.[16]

Ideally, the R_t and $F-\phi$ devices used should involve identical rock volumes. However their design and dimensions are determined to a greater or lesser extent by other considerations, discussed in Section IIIC. As will be shown in that Section, the minima volumes involved vary considerably in shape and dimensions, from device to device; without exception, $F-\phi$ devices involve volumes much closer to the well bore than those involved in R_t measurements; and, in general $F-\phi$ devices can be built with a finer vertical resolution than R_t devices.

The ideal requirement for identical R_t and $F-\phi$ yielding volumes therefore cannot be met (save perhaps in very rare, fortuitous cases). Obviously, the damage caused to the evaluation by the almost universal transgression of that re-

[16] Carbonate reservoirs and more generally all heterogeneous formations and complex lithological sequences rarely revealed their true worth to conventional resistivity logs which, until 1949 approximately, were the only sources of R_t and $F-\phi$ data available. These logs required such long spacings in order to overcome or circumvent the effect of invasion that they could be satisfactorily analyzed only in very thick homogeneous volumes. With the advent of focused R_t and $F-\phi$ logs, the seemingly endless, hopelessly tangled transition patterns of conventional logs disappeared and representative points and segments multiplied as if by magic. Carbonate reservoir evaluation through well logs finally had come into its own.

quirement is nil in thick homogeneous rock volumes of wide areal extent, greatest in unstratified, highly heterogeneous carbonate rocks.[17]

In thick homogeneous rock volumes or in stratified rocks, whether sandstone or carbonate, where ϕ, F and S_w can be considered constant within the reach of the R_t devices used, the broadest, soundest statistical evaluation will always be obtained through the use of the smallest $F-\phi$ devices suitable for the conditions under study, regardless of the dimensions imposed on the R_t device. This principle finds its basis in the preceding considerations on well log responses, and in the fact that an R_t log can neither be fully deciphered nor interpreted in terms of water saturation without the knowledge of F or ϕ. Thus, a stratified reservoir must first be divided in its constant $F-\phi$ component layers, only after which the water saturation may be determined in those layers whose thicknesses exceed the minimum required by the R_t log used. The finer vertical resolution of the $F-\phi$ device used insures that all the water saturation determinations permitted by the R_t device used can be made, if desired. Should the $F-\phi$ log have a coarser vertical resolution than the R_t log, all volumes thicker than the minimum thickness required by the R_t log but thinner than that required by the $F-\phi$ log completely escape analysis and are irretrievably lost for the statistical evaluation of the reservoir.

The use of a $F-\phi$ log which is more "detailed" than the R_t log may become mandatory in some cases. In Section IC it was seen that in many reservoirs the water saturation around a given level decreases as the porosity increases, and vice versa. (The example of a Type I-BCD reservoir was cited in which the product ϕS_w at a given level in fact remains practically constant.) Equation (11) indicates that R_t, and the R_t log readings, may change very little in all reservoir volumes where this situation occurs, with the result that the $\phi-S_w$ relationship cannot be established with certainty, unless the $F-\phi$ device can break down such volumes into their constant $F-\phi$ components.

IIIC. ELEMENTS FOR THE DESIGN OF LOGGING PROGRAMS FOR CARBONATE RESERVOIRS, AND FOR THE USE OF THE RESULTING LOGS

Every logging technique is designed for use in rotary wells drilled with water-base muds, because of the overwhelming preponderance of such wells today. This section is primarily limited to a discussion of logging programs and log uses in such wells, when their objective is a carbonate reservoir. A few words on holes drilled with oil-base muds or air or gas will then follow.

Carbonate Reservoirs Drilled with a Water-Base Mud

Any reservoir drilled with a water-base mud is subjected to flushing and invasion by the drilling mud and/or mud filtrate, under the pressure differential maintained between the mud column hydrostatic pressure and the reservoir pressure. The invasion comprises two phases: a temporary one, in which the mud and/or

[17] This subject is discussed in some detail in Section IIID.

mud filtrate invade the reservoir downwardly ahead of the drilling bit, and an after-drilling phase of particular interest here, in which the invasion proceeds outwardly from the borehole through the exposed portion of the reservoir, for as long as the pressure differential exists.

In a carbonate reservoir, the invasion process and its influence on logging programs and log uses differ widely with the rock and pore structure types involved. Four main cases, each corresponding to a single, preferentially water-wet rock type,[18] will be reviewed:

A. *Granular Type III reservoir volumes without fissures*, in which the sweeping action of the invading mud filtrate causes an effective mass displacement of the movable reservoir fluids away from the borehole. It may be helpful to state at once that this rock type is that for which all logging and log analysis techniques have been primarily designed.

B. *Chalky Type II reservoir volumes without fissures*, which the mud filtrate barely invades.

C. *Granular Type III or chalky Type II reservoir volumes cut or divided by fractures*, in which the invasion involves swift penetration of the fracture system by the mud and slow capillary imbibition of mud filtrate by the matrix blocks between fractures.

D. *Compact crystalline Type I reservoir volumes* which owe their productive capacity to their *secondary porosity*, principally or exclusively, and in which the invasion process and logging conditions depend upon the origin of that porosity.

Case A. Granular Type III Reservoir Volumes

These volumes have a pore structure which is primary in origin and, except for minor differences noted in Section IA, is similar to that of sands and sandstones. They therefore lend themselves quite well to evaluation through the relationships of Section IIIA. A range of 1.8 to 2.0 is most often found suitable for both exponents m and n.

Not unexpectedly, the invasion process and logging conditions are very similar to those in sands and sandstones. Statistically however, Type III rocks rarely, if ever, attain the high porosities found in certain sands. The result, explained momentarily, is that they invade more deeply than sands as a rule.

In a granular reservoir volume, the mud leaves its solid particles on, or within a very short distance from, the walls of the borehole, and the mud filtrate invades the volume through its entire intergranular network. The result of this action, if not the process, is similar to that of an efficient water flood. Most of the movable reservoir fluids are displaced farther into the reservoir volume.[19]

[18] It will be remembered, of course, that rock and pore structure types often grade into one another within a reservoir.

[19] If all the pores throughout the entire volume were perfectly identical in shape and size, all the hydrocarbons would be displaced from the invaded zone. Such perfection is never achieved in nature, or even in the most carefully prepared synthetic laboratory models. As a result, hydrocarbons can never be completely displaced by a water flood process, or by the invasion process discussed here.

After the first hour or so, the invasion process is controlled solely by the mud filter cake, because the latter, once solidly anchored, possesses a permeability which is very much lower than any permeabilities found in producing granular rocks. Thus, over a given period of time, a volume is invaded to a distance or radius which is an inverse function of its porosity. (The higher the porosity, the smaller the radius of invasion, all other factors being equal.) Type III rocks rarely have a porosity in excess of 20 percent and, when drilled with an "average" mud, are invaded by at least a few inches, counted from the walls of the borehole, within eight hours or so. Should their porosity be only 10 percent, the invasion "front" would be 2 to 3 ft from the walls in that much time. Obviously, the above figures have no other purpose than to indicate an order of magnitude.

The invaded zone developed by logging time does not have a constant fluid distribution, by any means. At least two sub-zones are recognized. The first, immediately behind the mud filter cake, is the so-called "flushed annulus" in which the interstitial water and all but a residual hydrocarbon saturation RHS have been displaced by the mud filtrate.[20] The second, extending from the outer front of the flushed annulus to the outer boundary of the invaded zone is a sub-zone of transition in which the fluid distribution changes from that of the flushed annulus to that of the virgin reservoir. In the nomenclature of well logging, R_{xo} and R_i denote the resistivities of the flushed annulus and the invaded zone as a whole, respectively. There is no particular symbol for the transition sub-zone.

Application of equation (11) to the flushed annulus gives:

$$R_{xo} = FR_{mf}/(1 - RHS)^n \tag{14}$$

which yields the formation resistivity factor F of the flushed annulus:

$$F = R_{xo}(1 - RHS)^n/R_{mf}. \tag{15}$$

Determination of the "True" Resistivity R_t of a Virgin Granular Reservoir Volume

It is seen that R_t measurements require the use of devices which somehow reach and "investigate" the virgin reservoir beyond, and in spite of, the invaded zone and mud column. Theory and experience concur to show that only properly designed focused R_t devices can achieve this feat in carbonate reservoirs, under most conditions. There are two main types: induction and laterolog or guard.

Induction Log

This log is used in fresh water-base muds or more generally in situations where the R_{mf}/R_w ratio is high, preferably above 10. (It is also the only R_t log usable in oil-base muds and holes drilled with air or gas.)

Principle and Effect of Invaded Zone. An induction device subjects the invaded zone and the virgin reservoir to a focused electromagnetic field. The conduc-

[20] This is for the case of a clean reservoir, considered all along in this paper. In shaly and silty reservoirs, there is considerable evidence that some interstitial water remains in place in the flushed annulus.

tivity signal recorded by the log is a complex function of (1) the spacing between the coil emitting the field and the coil receiving the signal and (2) the radial fluid distribution from the borehole to the virgin reservoir. Basically it corresponds to a measurement in parallel of the resistivities R_i and R_t. Thus the contribution of the virgin reservoir to the signal increases with the ratio R_i/R_t, or the ratio R_{xo}/R_t. This is why induction logs work best with high R_{mf}/R_w ratios.

An increase in the spacing also increases the relative contribution of the virgin reservoir to the log signal, but impairs the vertical resolution of the log, for reasons stated in Section IIIB.

Vertical Resolution. The minimum thickness which a volume must have to yield a representative point or segment on the log depends upon the contrast between the conductivity of the volume and the conductivities of the volumes adjacent to it. This is in accord with the teachings of Section IIIB. For the 40-inch induction log, the minimum thickness is 6 ft if the volume studied is less conductive (more resistive) than the volumes above and below it, 4 to 5 ft if the reverse is true. The 60-inch induction log requires correspondingly larger figures. Logging companies running these logs have some charts available for thickness corrections in thinner volumes. Their usefulness is somewhat limited.

Clearly, induction logs require rather excessive minimum thicknesses for statistical carbonate reservoir evaluation.

Laterolog-7, Laterolog-3 and Guard Log

These logs are used for R_t determinations in salty muds or more generally in all situations where the R_{mf}/R_w ratio is below 5 or better still 3. They cannot be used in oil-base muds or in empty holes.

Basically laterolog and guard devices force the logging current to flow outwardly from the borehole within two surfaces roughly perpendicular to it. The thickness of the current slice or disc between the two surfaces is equal to the distance between the monitoring electrode pairs in a laterolog-7, to the height of the central electrode in the laterolog-3 and guard devices.

Effect of Invaded Zone and Correction for Invasion. The current must go through the invaded zone before it reaches the virgin reservoir. For moderate diameters of invasion and R_{xo}/R_t ratios, the apparent resistivity R_a obtained with a laterolog-7 is given approximately by:

$$R_a = 0.633(\text{Log } D/d)R_{xo} + (1 - 0.633 \text{ Log } D/d)R_t, \tag{16}$$

in which d is the diameter of the hole and D the diameter of the invaded zone. Adaptations of equation (16) for laterolog-3 and guard devices are also available. R_{xo} and R_t can be replaced in equation (16) by their basic expressions, equations (14) and (11) respectively, giving:

$$R_a = (0.633 \text{ Log } D/d)FR_{mf}/(1 - RHS)^n + (1 - 0.633 \text{ Log } D/d)FR_w/S_w^n. \tag{17}$$

Equation (17) and equivalent forms thereof for laterolog-3 and guard devices may

easily be transformed to show that the smaller the ratio R_{mf}/R_w, and the smaller the depth of invasion or the ratio D/d, the nearer the apparent value R_a to the R_t value sought. In practice, equation (17) and its equivalents are used in nomographic forms. Figure 17, adapted from a Schlumberger chart, shows a typical nomograph used for laterolog-7 and laterolog-3 equipments, assuming RHS = 20 percent in the flushed annulus. Starting with a value FR_{mf}/R_a entered on the left edge of the left grid, a water saturation S_w corrected for invasion is obtained from the right grid, at the appropriate saturation exponent line, for the R_{mf}/R_w ratio obtaining in the reservoir under study.

Vertical Resolution. The vertical resolution of properly designed laterologs and guard logs is primarily determined by the thickness of the current disc, which is largely a matter of design. The first versions of the laterolog-7 utilized thicknesses of 32 inches and 24 inches, definitely too large for the great majority of carbonate reservoirs. A laterolog-3 with a 6-inch disc and the guard log with a 3-inch disc rapidly took over in most areas. The 6-inch laterolog-3 was recently superseded by a conductivity laterolog-3 with admittedly superior response characteristics but which needlessly and most regrettably uses a 12-inch disc. It can only be hoped that this excellent design will soon be available with a 6-inch disc, reportedly quite feasible.

Laterolog-3 and guard type devices give the finest, best documented R_t evaluations possible today, and should be used whenever the R_{mf}/R_w ratios are sufficiently low. They would do an even better job if usable charts for thickness corrections were available. However, a feeling, which this writer does not share, apparently prevails that they do well enough without this refinement.[21]

Desirability of Low Filtrate Loss Muds

One feature common to induction and laterolog or guard logs must be emphasized. They suffer from excessive invasion. Their optimum use requires that (1) care be taken to avoid excessive mud filtrate loss, and (2) the logs be run before the invasion has proceeded too far.

Actually these are not requirements peculiar to carbonate reservoirs. A low filtrate loss mud not only benefits the log analysis, but also reduces the physical damage to the borehole (excessive mud filter cake) and to the reservoir ("skin effect"), thus permitting better, surer, and cheaper completions.

Logging of Formation Factor F and/or Porosity ϕ in Granular Volumes

Four different types of $F-\phi$ logs may be used in granular reservoir volumes: microresistivity, acoustic, neutron-induced and gamma-induced or density logs.

In theory all four types accomplish the same end, thus only one is normally used in a given well. As will be seen shortly however, situations arise where two may be most helpful or even indispensable.

[21] Repeat runs of high and low resistivity intervals should be made to check the stability of these tools, which may become poor due to current leakage or other malfunctions.

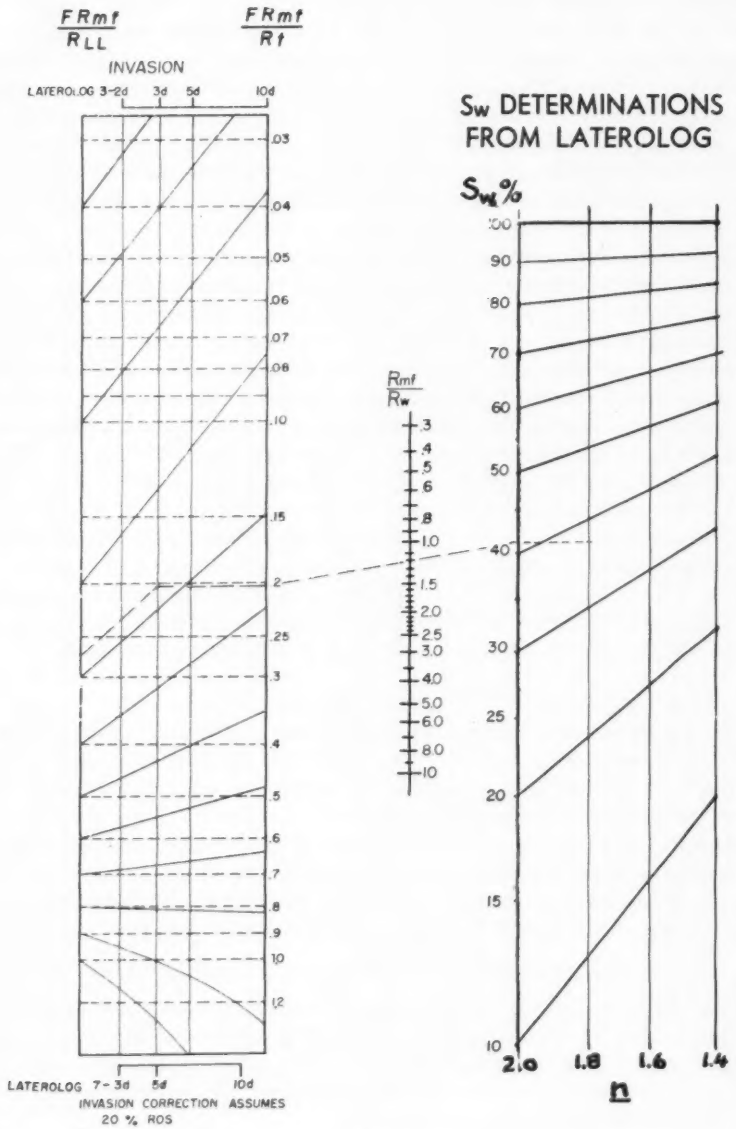

FRmf / RLL
FRmf / Rt
INVASION
LATEROLOG 3-2d 3d 5d 10d
.03
.04
.05
.06
.07
.08
.10
.15
.2
.25
.3
.4
.5
.6
.7
.8
.9
1.0
1.2
LATEROLOG 7-3d 5d 10d
INVASION CORRECTION ASSUMES
20 % ROS
Rmf / Rw
.3
.4
.5
.6
.8
1.0
1.5
2.0
2.5
3.0
4.0
5.0
6.0
8.0
10
Sw DETERMINATIONS
FROM LATEROLOG
Sw %
100
90
80
70
60
50
40
30
25
20
15
10
2.0
1.8
1.6
1.4
n

FIG. 17.

1. Microresistivity $F-\phi$ Devices and Logs

Principle. Under proper conditions of use, these devices and logs yield the resistivity R_{xo} of the flushed annulus, whenever the latter exceeds three to four inches in thickness.[22] From R_{xo} the formation resistivity factor F of the annulus is derived through equation (15), previously introduced:

$$F = R_{xo}(1 - RHS)^n/R_{mf} \tag{15}$$

provided R_{mf}, RHS and n are known. n is determined by ways and means discussed in Section IIIA. R_{mf} is obviously a most critical factor and should be measured on carefully selected mud filtrate samples.

Estimation of RHS. RHS, strictly speaking, is unknown. In practice, in Type III reservoirs, RHS can almost always be estimated from core residual oil saturations, when available, or through examination of the rotary cuttings in terms of pore size distribution, saturation and staining (if oil-bearing), taking also into account the structural elevations (when known) of the volumes analyzed and the nature of the hydrocarbons which they contain.

RHS varies widely with the area and reservoir involved and at times is known to reach 50 percent or more of the pore space. Evidently, local experience plays a critical role here.

Effect of Error on RHS Range. Use of Other $F-\phi$ Log in Wildcat Wells. Equation (15) shows that a large error on RHS, say using a 20–30 percent instead of a 0–10 percent range, will not seriously alter the diagnosis of the potential value of a reservoir volume, especially if evaluated with many other volumes, except in border line cases. The loss of accuracy may be cured in time through the use of core data, or by adding to the logging program one of the other $F-\phi$ logs, which are affected by RHS either not at all or only to a very minor degree. The correct RHS range is that which brings about agreement between the F or ϕ values derived from the two logs. Should this RHS range be on a par with regional standards, a hydrocarbon accumulation of some merit is most probably present. The use of two such $F-\phi$ logs is therefore particularly advisable in rank wildcats which are not cored.

Advantages of Microresistivity Devices in Granular Reservoirs. 1. *Direct Determination of F.* Contrary to other devices, microresistivity devices yield formation resistivity factors F, from which may be deduced R_o values and resistivity indices $I = R_t/R_o$ unaffected by any error made on the exponent m linking F and ϕ. This may be important in wildcat wells. 2. *Maximum Vertical Resolution.* Thanks to their very short spacings (one to two inches), these devices provide the most detailed study possible today of $F-\phi$ properties, by 3-inch increments, if desired. They always satisfy the requirement that $F-\phi$ logs have a vertical

[22] As previously intimated, the annulus thickness increases with the mud column-reservoir pressure differential, the permeability of the mud cake, and the time elapsed between drilling and logging, and decreases as the reservoir porosity increases.

resolution at least as fine as, and preferably finer than, that of the R_t log used.[23]

Non-Focused Types (Micrologs, Contact Logs, Permalogs, etc.) These logs must be considered as inadequate for Type III reservoirs with porosities below 20–25 percent. They can however be very useful in shaly reservoirs, due to their ability to detect (not measure) permeabilities in excess of 0.1 millidarcy.

Focused Microresistivity Devices (Microlaterologs, $F_o - R_{xo}$ Logs). These are the only microresistivity devices suitable for the evaluation of Type III reservoirs and indeed many sandstone reservoirs. However they require attention and outside assistance on two points:

(a) They yield true R_{xo} values only as long as the mud cake thickness MCT does not exceed approximately $\frac{3}{8}$ inch. Above half an inch corrections become important, and elusive. Consequently, MCT must be known. Under most conditions it may be estimated through a microcaliper log, commercially obtainable simultaneously, or a non-focused microresistivity log (whose interpretation yields MCT as a by-product).

Because of the effect of MCT, the use of focused microdevices is largely limited today to holes drilled with salt muds, which, when reasonably well controlled for filtrate loss, yield thin to very thin mud cakes. Nothing, however, prevents using focused micro tools in fresh mud, whenever the mud cake is thin enough.[24]

(b) Focused microresistivity logs at present comprise only one curve and of themselves cannot distinguish pervious from impervious volumes. Thus, they must be interpreted in the light of other logs indicating porosity-permeability development, or PPD for short. These logs may be one or more of the following: S.P. log, interpreted according to the teachings of Doll, gamma-ray log, microlog, or microcaliper log. The gamma-ray log does not indicate PPD, but often may be related to PPD within a field, in a manner specific to the field. The microcaliper log detects mud cakes, sure indications of at least 0.1 millidarcy permeabilities, and measures their thicknesses, wherever the borehole preserves a cylindrical shape. This is fortunately the case in many carbonate reservoirs. If however the hole is enlarged, either due to crumbling of the rock or to whipping by the drill pipes, any mud cake present may remain undetected.[25]

2. Velocity, Acoustic, or Sonic Devices and Logs

Principle and Vertical Resolution. Acoustic devices normally measure the shortest time ΔT (time of "first arrival") taken by a sound wave to travel the

[23] Actually, microresistivity devices are macroscopic devices involving at least 50 cu in of material, which is at least as large as a full diameter core.

[24] The "proximity" log, a new type of focused microresistivity log, can cope with MCTs of 1 inch or more. It requires thicker flushed annuli, but that should not be a problem in most Type III reservoirs.

[25] The microcaliper log also serves another very useful function in showing the general shape of the hole: knowledge of this item permits surer casing cementing and better control of completion procedures.

distance of the spacing between transmitter and receiver in the one-receiver type, of the span between receivers in the two-receiver type. Either spacing or span is designated here by the letter L.

Normally again, in a homogeneous rock, the sound waves travel the distance L fastest through the rock annulus closest to the borehole. In a Type III reservoir, this annulus (the thickness of which depends partly upon the wave length used) may generally be assumed to be comfortably within the flushed annulus.

Commercially available are 1-ft, 2-ft and 3-ft spans for two-receiver logs, 6-ft and 9-ft spacings for one-receiver logs. The 1-ft span is mandatory in carbonate reservoirs, permitting the evaluation of homogeneous thicknesses slightly exceeding 1 ft.

Effect of the Hole Size. The response of one-receiver acoustic logs depends on the hole size, while that of two-receiver logs does not, as long as the receivers are in the same hole size. Two-receiver logs are therefore preferable in a volumetric evaluation. However, they exhibit sharply marked "zig-zag" or Z-shaped transition patterns at hole size changes. Both one- and two-receiver type logs should be interpreted in the light of a microcaliper log. In the absence of the latter, the S.P. log or the gamma-ray log should be consulted to identify any shale streaks present. As well known, many shales show a marked tendency to crumble or disintegrate during drilling operations.

Interpretation of Acoustic Logs in Terms of Porosity ϕ. The time interval ΔT has been found to be related to the total porosity ϕ of granular porous media. The "time average" relationship first proposed by Wyllie, and now universally used, reads:

$$\Delta T/L = 1/V = \phi/V_F + (1 - \phi)/V_S, \tag{18}$$

where $V = L/\Delta T$ is the measured average sound velocity, and V_F and V_S are the velocities of the interstitial fluid and the solid rock framework, respectively, in the annulus. All velocities are expressed in ft/sec.

Interstitial Fluid Velocity V_F. Effect of Residual Oil and Gas Saturation in Annulus. Detection of Gas Zones. When the invasion is sufficiently deep, V_F may be taken equal to V_{mf}, velocity of the mud filtrate, at the pressure and temperature considered. V_{mf} usually ranges between 4,900 and 5,500 ft/sec. Strictly speaking, account should be taken of any residual hydrocarbons in the annulus. Equation (18) however shows that their effect is small, (actually of a third degree order), as long as the porosity does not exceed 15 percent.

In gas-bearing portions of a reservoir, V_F may be more difficult to determine. Gas does not transmit sound nearly as well as oil or water, and usually complicates the interpretation. If V_F is taken equal to V_{mf}, too high porosities will normally result. This feature may be turned to advantage for locating gas-bearing zones: another $F-\phi$ log is also run, either a microlaterolog whose readings are not drastically altered by gas, or a neutron log, which tends to yield too low porosities in such zones.

Solid Rock Framework Velocity V_S. Laboratory investigations indicate that V_S depends primarily upon the mineralogical composition and, to a degree not yet fully understood, the pore structure, pressure and temperature of the rock. Values between 17,000 and 26,000 ft/sec have been quoted in the literature. Carbonate rocks stand in the upper half of this range, with limestones mostly in the 21,000 to 23,000 range, and some dolomites approaching 26,000. Sands and sandstones occupy the lower half of the total range.

Selection of the correct V_S value is undoubtedly one of the major problems to be overcome in acoustic logging. Ideally V_S should be measured in the laboratory. In everyday practice however, this is very rarely done. The log user selects a V_S value, or preferably a V_S range, on the basis of the lithology of the rotary cuttings or cores and of his experience with similar cases.

Linear Response of Acoustic Logs. Effect of Error on V_S. Equation (18) shows that for a given fluid and a given rock, ΔT increases linearly with porosity. This feature is doubly attractive: first, the ΔT scale can be transformed in a linear porosity scale; second, the porosity resolution is constant throughout the porosity range. Figure 18, reproduced from SSC Technical Bulletin 2A, illustrates these points for $V_F = 5{,}200$ ft/sec, and six V_S values ranging from 17,500 to 26,000 ft/sec. The same figure also clearly shows that an error on V_S affects the determinations much more in the low porosity than in the high porosity range.

Adequacy of Time Average Relationship. In its present form equation (18) has yielded porosity values comparable with many porosities measured on cores or through other $F-\phi$ logs. However, it is realized that equation (18) and its representations, such as Figure 18, may be somewhat too simple for rock types markedly departing from the granular.

Indirect Determination of F. Effect on S_w *Determinations.* Acoustic logs (and the neutron-induced and gamma-induced logs to be reviewed shortly), yield ϕ values, which must be converted to F values before water saturation determinations can be made. Thus, the latter are affected by any error made in the selection of the formation resistivity factor exponent m. See Section IIIA.

Location of Rock Mineralogical Types by Acoustic and Microresistivity Logs. The marked dependence of ΔT on the nature of the minerals composing the solid framework can be used to advantage for accurately locating different rock types in carbonate reservoirs, or, more generally, non-clastic sediments.

In this application, a microlaterolog-microcaliper log is also run. In each identifiable homogeneous reservoir volume, the acoustic log porosities obtained for the different V_S values called for by the rock types seen in the rotary cutting examination are tabulated on the same line as the porosities derived from the microlaterolog for the different exponents m called for by the same examination. The result is a double table of possible ϕ values for different V_S and m values, covering the height of the reservoir. Reasoned confrontation of the two sets of porosity values normally leads to a set of narrow, compatible V_S and m ranges for each volume. The V_S ranges are then interpreted in terms of mineralogical composition.

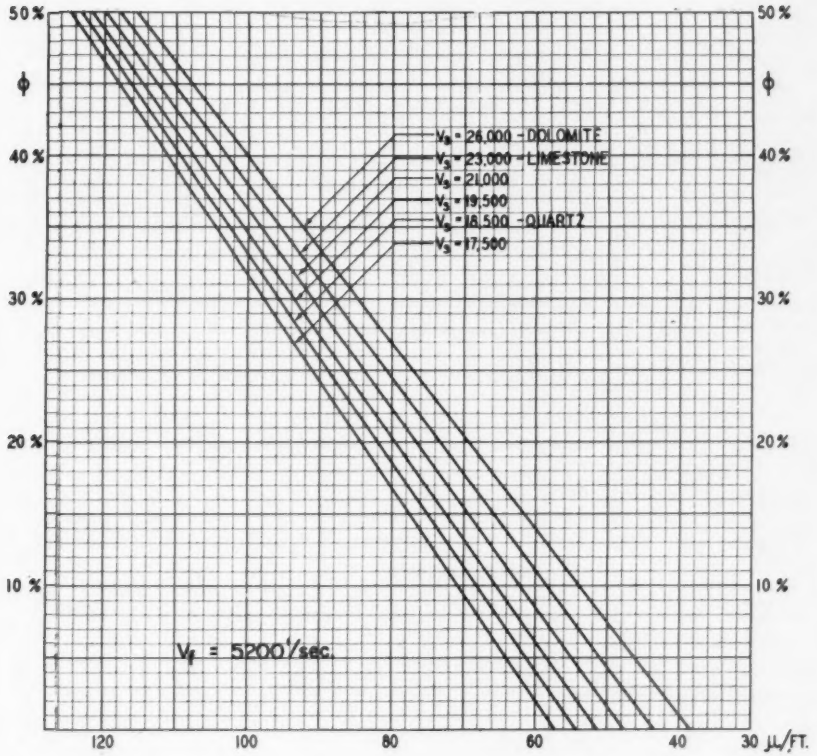
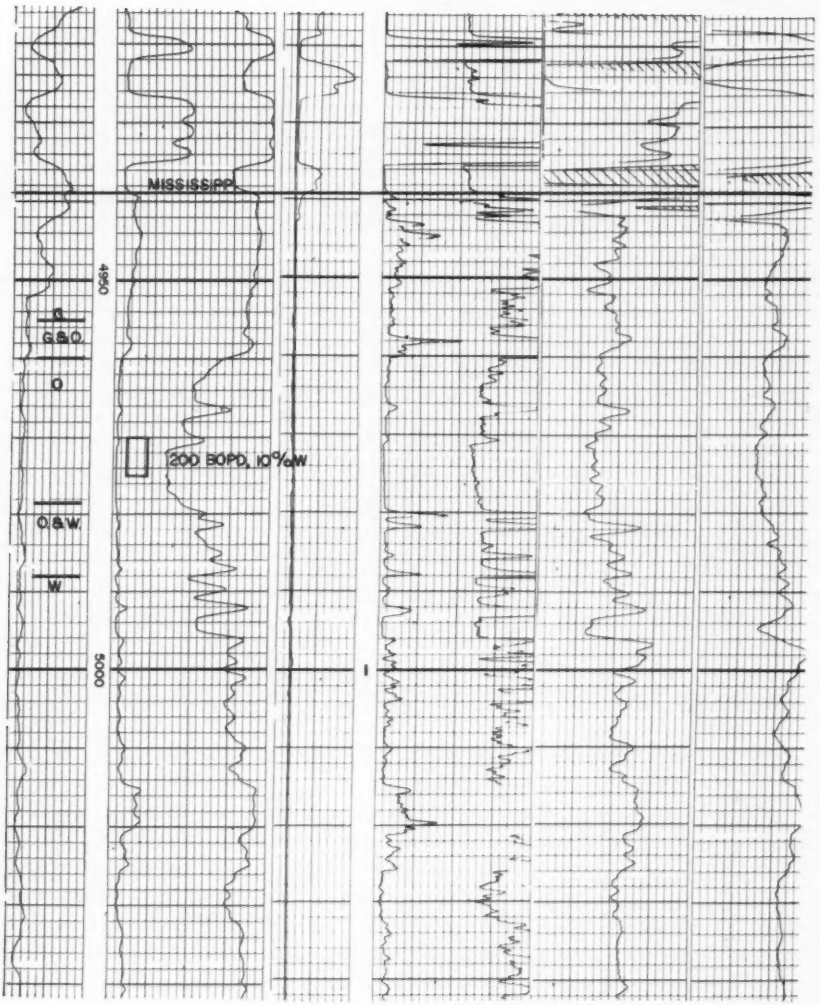


FIG. 18. Transit time vs porosity.

Figure 19 shows the complete set of logs obtained in a well drilled through the Mississippian age reservoir of the Nichols Field of Kiowa County, Kansas.[28] On the basis of structural and stratigraphic studies and of log, drill stem test and production data obtained in offset wells to the west and to the northeast, the highest point expected for the oil-water contact in this well was between 4,995 and 5,000 ft. The reservoir above these depths was subjected to three carefully staged drill stem tests, with small recoveries of oil and oil-cut mud, no water, and abnormally low pressures, quite disappointing by field standards. Detailed cutting examination indicated the presence of two main rock types: (a) a mixture of vitreous, fossiliferous and tripolitic cherts with a relatively coarse pore structure including solution voids of pinpoint to small vug size, from the top of the reservoir at 4,943½ ft to approximately 4,960 ft, and from approximately 4,980 to below 5,000 ft; and (b) a slightly cherty, fine-grained sucrosic dolomite

[28] This well is Well C of Figure 2.



FRANCIS AND KAISER · PARKIN "C" NO. 4
SEC 5 . 30S 18W KIOWA COUNTY, KANSAS

FIG. 19. Mississippi. Gamma ray. Laterolog 3. Microcaliper. Microlaterolog. 1′ Sonic. 3′ Sonic.

facies, somewhere between the approximate depths of 4,960 and 4,980 ft. Use of a microlaterolog and 1- and 3-ft sonic logs, in the manner previously described, led to near exact location of the main dolomitic intervals at 4,961–4,965 ft, 4,967½–4,979½ ft, 4,995–4,997 ft. Interpretation of the laterolog followed, and placed the oil-water contact at or near 4,979 ft, at least 16 ft higher than anticipated. This 16-ft rise was due to the fine-grained dolomitic facies occurring only in this well, and at the depths noted. The interval 4,970–4,975 ft was perforated, cleaned with mud acid and lightly fractured, for a pumping test of 200 BOPD with 10 percent water. The small water cut is also obtained in the offset wells, completed earlier at subsea levels 10 to 15 ft lower. This example is but one illustration of the necessity for gathering and closely integrating all the necessary well data, whatever their sources, when dealing with carbonate or non-clastic reservoirs.

Geometrical Effects. As stated in Section IIIB, acoustic logs are subject to geometrical effects in reservoir volumes thinner than the spacings. Such effects appeared in the well of Figure 19, in isolated occurrences or in series of several, in a number of intervals, especially on the 3-ft log (e.g., at 4,952–4,953, 4,960–4,966, 4,968.5–4,970.2, 4,975–4,978, 4,979.5–4,991.5, 4,996–4,997, 5,000–5,004, 5,022.5–5,026, 5,027–5,032 ft).

3. Neutron-Induced Logs

Principle of Neutron-Induced Log. A neutron-induced log, or neutron log for short, is a record of a selected portion of the radiation induced in formations through their bombardment by fast neutrons. The source of fast neutrons and the detector intercepting the induced radiation are mounted in the device, the space between them usually being occupied by radiation-shielding material.

Neutron devices designed for porosity evaluation utilize that portion of the induced radiation spectrum which is predominantly affected by hydrogen. A clean (shale-free) formation contains this atom only in its interstitial fluids, gas, oil and water, that is only in its pore space. The number of hydrogen atoms in gas-filled porosity varies with pressure (see further), but is practically constant in liquid-filled porosity, whether the liquid be oil or water. The neutron log then measures the total porosity, in clean, liquid-filled formations.

Statistical Nature of Measurement. As well known, all nuclear radiations are statistical phenomena, i.e., they exhibit variations of intensity about their mean values, as time passes. To smooth out the log, a "time constant device" is included in the circuitry between the detector and the log recorder. This device has the drawback to increase the thickness of transition patterns at boundaries between volumes of different hydrogen contents, as explained under Vertical Resolution.

Relationship between Liquid-Filled (Clean) Porosity and Log Response. The spacing source-detector in current designs is purposely made such that the log

response in counts per second, CPS, decreases as the porosity increases. The response in an open borehole is of the general form:

$$CPS = A - B \operatorname{Log} \phi, \tag{19}$$

in which A and B are positive quantities, which reflect the combined influence of all of the following elements: (a) type of induced radiation selected for detection (essentially, the designer must choose between gamma rays of capture and epithermal neutrons); (b) source, detector and circuitry design; (c) spacing, mechanical design and diameter of tool; (d) composition and diameter of the fluid column in the hole; (e) position or "eccentricity" of the device in the hole; (f) chemical constitutions of the rock matrix and interstitial fluids.[27]

With all the above elements fixed, and depending primarily upon elements (a), (b) and (c), A and B are found to be very nearly constant, or slightly variable, causing the graphical representation of equation (19) on a semi-log paper to yield straight lines, or slightly curved lines, respectively (the porosity being reported on the log scale).

Figure 20, reproduced from Winn, shows the semi-log graphs obtained with a commercial tool in uncased test holes filled with fresh water, in limestone blocks of known porosities saturated with fresh water, for three hole sizes and two positions of the tool.

Calibration graphs relating ϕ and CPS for a given tool, such as those of Figure 20, may be obtained in four ways: (1) that already mentioned of calibration in specially designed test holes. This method was recently standardized by the American Petroleum Institute, and the required facilities constructed under API auspices on the campus of the University of Houston, Texas; (2) in one or more holes of given size in a given field, plots of CPS against weighted average porosities of cores, preferably full diameter cores. This method has been used successfully for many years in numerous carbonate reservoirs throughout the world; (3) in holes of given size in a field, plots of CPS against porosities derived from other $F-\phi$ logs. Since the interpretation of all logs involves some assumptions or simplifications, this method usually is not as accurate as the first two; (4) in a hole under study, assignment of arbitrary porosities, based on local experience, to the densest rock and the most porous formations present. The latter will almost always be shale beds, which, in this method, are necessarily viewed as porous-permeable. In a second step, a standard logarithmic scale is fitted to the two arbitrary values, if A and B can be assumed constant for the tool and conditions involved; if not, a suitably deformed log scale is used. This fourth method, requiring no outside assistance, is very commonly resorted to in the field.

Conditions of Interpretation of Neutron Logs. Clearly, the reliable calibration of a neutron log in terms of porosity in a given hole at the very minimum requires

[27] Logs using epithermal neutrons are generally affected very little by element (*f*), except for certain shales.

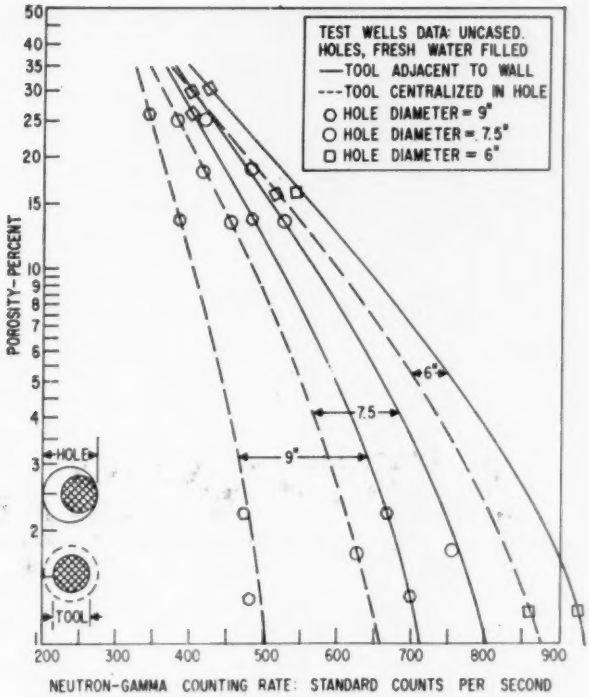


FIG. 20. Neutron log response vs porosity.

that (1) the fluid column preserve a uniform composition and that its diameter be known; and (2) the nuclear device maintain the same eccentricity with respect to the walls of the hole, through the entire height of the reservoir. Although these requirements have long been recognized, most logs are still run today in uncalipered holes and without fixing the eccentricity of the tool. This practice hopefully relies on two empirical observations: first, many carbonate rocks are mechanically competent and a hole drilled through them remains essentially to gauge; second, most every hole is sufficiently off true verticality to cause a device to ride against its walls. There is however no guarantee that either condition obtains in any particular interval of interest.

In any case, without a microcaliper log, there is no way of correcting at least approximately for any mud filter cake present. Even a thin mud cake destroys the direct contact between the device and the walls, and affects the log response significantly, as seen on Figure 20 for instance. Figure 21 shows the S.P. log, microlaterolog, microcaliper and neutron logs obtained in a limestone of Devo-

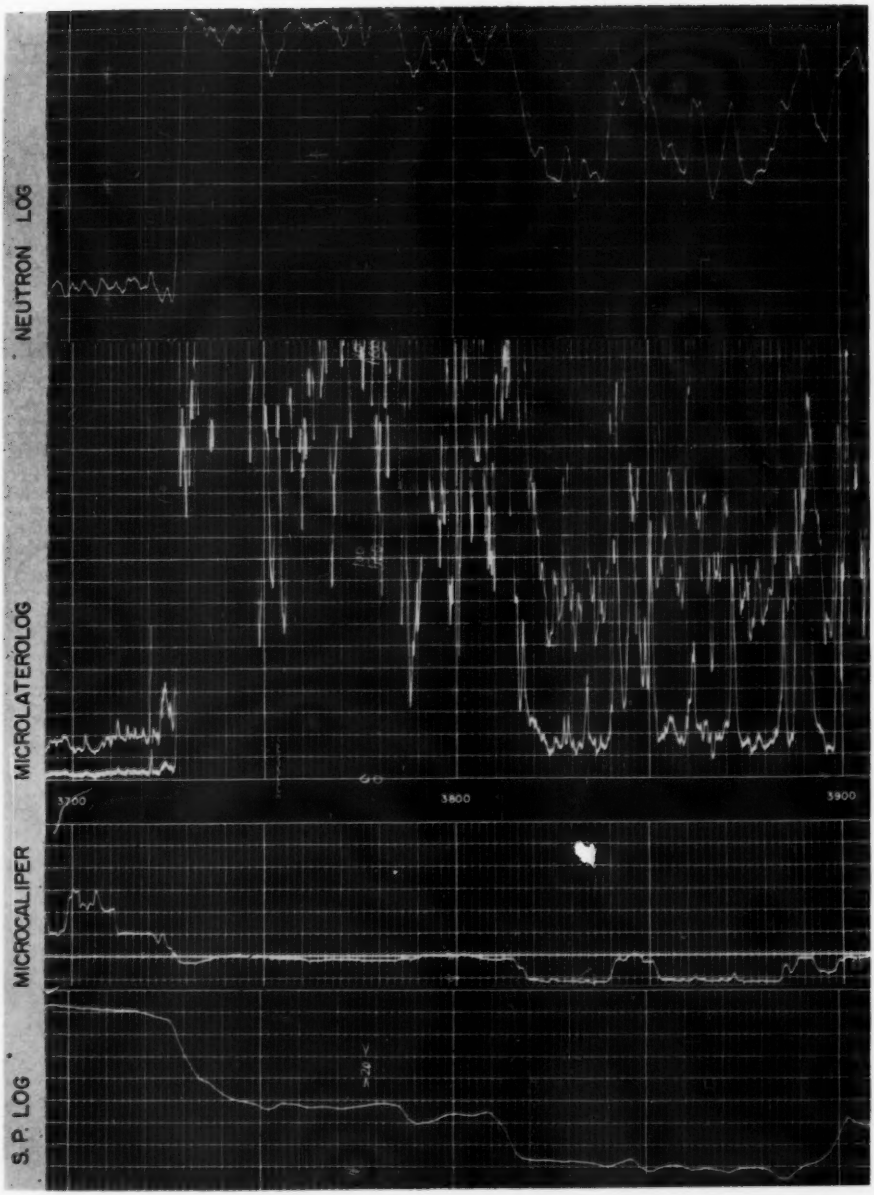


FIG. 21. Slave Point Formation, Northwest Territories of Canada.

nian age penetrated by a well in the Northwest Territories of Canada. A very low water loss mud was used, but weather and other conditions beyond the operator's control resulted in mud cake thicknesses MCT of approximately $\frac{1}{2}$ inch, by logging time. As a result, the microlaterolog and neutron log, uncorrected for MCT, yielded maxima porosities in the 10.6–11.6 percent and 12.5–13.5 percent ranges, respectively. After applying the necessary correction, both logs gave essentially the same result: a porosity in the 7.5–8.5 percent range. Similar deviations and corrections were calculated in less porous intervals.

Interpretation in Gas-Bearing Reservoir Volumes. In such volumes, the number of hydrogen atoms depends on both porosity and gas pressure. At moderate pressures (usually meaning at moderate depths), it is appreciably less than if the pore space was liquid-filled, and the log, calibrated in terms of liquid-filled porosity, indicates too low a porosity.

Use is frequently made of this fact to locate gas-bearing zones in carbonate reservoirs at shallow or moderate depths. Another $F-\phi$ log is also run, either a microresistivity log, little affected by gas, or an acoustic log, tending to yield too high porosities in gas-bearing zones.

Vertical Resolution. The transition zone recorded across a boundary between two volumes of different hydrogen contents and/or porosities is the composite of a "static" transition pattern and of the "lag" introduced by the time constant device. The static pattern is the transition zone that would be observed if the log were recorded at extremely low speed. Straddling the boundary and divided by it half and half, it results partly from the non-negligible spacing (about a ft for most commercial designs), partly from the fact that the neutrons emitted by the source diffuse out some distance into the formation. For a 12-inch spacing, it averages 18 inches in thickness. The lag is the element which lengthens the transition zone to serious proportions. For instance, assuming a time constant of two seconds and a logging speed of 1,200 ft/hr, the time and depth lags required before a percentage of the difference between the two hydrogen contents is registered by the log are: 1.4 sec and $\frac{1}{2}$ ft for 50 percent; 2 sec (the time constant) and $\frac{2}{3}$ ft for 63.2 percent; and 6 sec and 2 ft for 95 percent. These thicknesses must be added to half the thickness of the static pattern. Thus, for the time constant and speed indicated, a volume must have a thickness in excess of 30 inches for the apparent reading therein to be within 5 percent of true value. Such thicknesses are entirely too large for many carbonate reservoirs. It is also seen that the association of a laterolog-3 or a guard log with a neutron log will never satisfy the requirement that a $F-\phi$ log have a vertical resolution at least as fine as, and preferably finer than, that of the R_t log used.

Conditions of Use in Carbonate Reservoirs. In view of its poor vertical resolution (and of its sensitivity to shale content), the neutron log is hardly the best $F-\phi$ log in granular reservoirs, especially thin ones. In the main, its use should be restricted to reservoirs whose total porosity may not, or cannot, be evaluated

correctly by more detailed $F-\phi$ logs. Reservoirs with sparsely distributed, poorly connected solution voids, and fractured reservoirs are two typical examples where the neutron log should be used. These will be discussed in Cases C and D.

Use of Neutron Log in a Cased Hole. As well known, nuclear logs can be run through casing and cement and this is indeed one of their most useful applications. However, neutron logs in cased holes are generally not reliable sources of porosity data, because the geometry of the ensemble logging device-casing-cement sleeve-formation is unknown and bound to change with depth.[28]

4. Density (Gamma-Gamma) Log

The device yielding this newest $F-\phi$ log comprises a source of gamma rays and, at a fixed distance (or spacing) above, a detector which intercepts the scattered radiation not absorbed by the rocks. This returned radiation is an inverse function of rock density. If the specific gravities of the constituent minerals and interstitial fluids are known, the log may be calibrated in terms of porosity.

To prevent gamma rays from the source from reaching the detector through the mud or the instrument, the device is forced against the walls of the hole, and heavily shielded. Correction for hole size and weight of mud must be made. A microcaliper log therefore is necessary.

The tool appears to have good possibilities for use in mechanically competent carbonate rocks, against the walls of which a good contact can be maintained. Since density is a fairly sensitive function of mineralogical composition,[29] the density log promises to be of great assistance where the problem of recognition and/or location of different mineralogical types in a carbonate reservoir is critical.

The minimum thickness that may be individually investigated slightly exceeds the spacing.

Case B. Chalky Type II Reservoir Volumes

Such volumes possess a fine to very fine primary pore structure, and generally high porosity associated with extremely low permeability. Average ranges for the exponents m and n are 1.7–1.9 and 1.9–2.1, respectively.

The invasion process is similar to that in Case A (Type III) rocks, except that the PPD favors the appearance of only a shallow invaded zone by logging time. Either the induction or the laterolog-guard technique yields R_t without difficulty. Porosity determinations are not easy, due to the tendency of these rocks to crumble and disintegrate during drilling operations, resulting often in an irregularly shaped hole. The neutron and density logs do not cope well with

[28] Mention should be made of a new combination log using high energy induced gamma rays and regular or thermal neutrons, the only log thus far designed for detecting oil behind casing. Both porosity and salinity should be high, and considerable time must have lapsed following setting of casing, to permit near restoration of the original fluid distribution in the invaded zone.

[29] Sandstone (clean, non-porous), limestone and pure dolomite have average densities of 2.65, 2.71 and 2.85, respectively.

this situation, and the neutron log does not resolve high porosities accurately. The flushed annulus is too thin for the microresistivity techniques. Thus a two-receiver acoustic device of short spacing, coupled with a microcaliper log, is usually the best choice.

Case C. Granular Type III or Chalky Type II Reservoir Volumes Divided by Fractures (Water-Wet)

In these volumes, the fractures generally have such permeabilities that they are swiftly invaded by the mud, when the hole reaches them. If they run in different directions and are numerous enough to divide the matrix in relatively small blocks, the latter find themselves promptly surrounded by mud on all sides. Thus, the entry of mud filtrate through one side of a block is opposed by the filtrate seeking entry on the opposite side. In the end, all that takes place is filtrate imbibition by the blocks, a slow process at best.

Neither the virgin fluid distribution nor the resistivity of the blocks is changed appreciably then, except perhaps on the edges. Unless the fractures are very numerous, the resistivity of the mud invaded zone will be little different from that of the virgin reservoir, and the R_t log will yield the latter resistivity without any correction for invasion.

The R_t signal however must be apportioned between the fracture and the block systems. There are two reasons for this.

a. The conduction of current does not follow the same laws in the two systems. The conductivity of the fracture system is roughly proportional to the water saturation S_{fw} therein, while that of the blocks is proportional to S_w^n, S_w being the water saturation in the blocks.

b. The productivity of a Case C volume depends upon the characteristics (porosity, permeability, water saturation) of its blocks, but the water-oil ratio will be controlled mostly by the saturation S_{fw} in its fracture system, and by the proximity of the volume to the oil-water contact.

Detailed discussion of the evaluation of Case C reservoir volumes through well logs lies beyond the scope of this paper. This much only will be said. Such an evaluation involves:

(1) Consideration of the frequency of the fracture system, i.e., the number of fractures per ft, or per yard. This determines whether or not the fracture system may be statistically represented in microresistivity measurements, and how the latter should be used in the evaluation. Needless to say, that frequency can only be estimated at best. However, fractures crossing the borehole may be roughly counted on an acoustic log, which shows them by excessively long ΔTs (due to sound wave reverberation across them), or on a microresistivity-microcaliper log. The frequency of vertical or near vertical fractures is largely a matter of conjecture.

(2) Consideration of the ratio R_{mf}/R_w. The best evaluations are possible when this ratio is unity, or nearly so.

(3) Determination of the total porosity ϕ of the bulk reservoir volume through a neutron log.

(4) Use of a microlaterolog or an acoustic log of short spacing if the frequency of the fracture system is low. Either one of these logs then yields the porosity ϕ_b of the blocks. The porosity ϕ_f due to fractures may then be approximated by subtracting ϕ_b from ϕ.

(5) Use of a microlaterolog if the frequency of the fracture system is so high that it may be statistically represented in a microresistivity measurement. In that case, the microlaterolog yields an approximation of the total porosity ϕ_w[20] occupied by water in the invaded zone. The quantity $(\phi-\phi_w)/\phi$ then yields an approximation of the hydrocarbon saturation in the blocks. In that case, the porosity ϕ_f of the fracture system may not be obtained.

(6) Verification of the conclusions reached through the study of the $F-\phi$ logs and of conditions in the invaded zone, by application of a general R_t relationship involving both the fracture and the block systems.

A logging program for Case C reservoir volumes, in short, includes: S.P. or gamma-ray log, R_t log, neutron log, microlaterolog and/or acoustic log, and microcaliper log.

Case D. Crystalline Type I Reservoir Volumes Endowed with Secondary Porosity

The matrix or primary rock is made of fairly dense to dense, crystalline limestone with low porosity and practically non-existent permeabilities. It often is 100 percent water-bearing. Such volumes owe their productive capacity mainly, often exclusively, to their secondary porosity.

Subcase D1. Secondary Porosity Due to Dolomitization

Pure dolomites are often classified with granular-sucrosic Type III rocks and with good reason. They are amenable to evaluation by the relationships of Section IIIA, with approximately the same ranges for the exponents m and n as for granular limestones. However, dolomitization is most frequently accompanied by solution, resulting in a widening of the two exponent ranges. (See D2 below)

Logging programs in pure dolomites are set by the same considerations and rules as those for granular limestones.

Subcase D2. Secondary Porosity Due to Solution

The invasion process and logging conditions basically depend upon the number or frequency of voids per volume unit, as well as upon their size.

(a) When the voids are quite numerous, well interconnected and not too large, the pore structure, fluid distribution and production characteristics are essentially those of granular reservoirs. The maximum void size for which this statement holds true is not easy to define. Insofar as log interpretation is concerned, experience tends to indicate that a wide range of frequencies and sizes,

[20] Also referred to as "porosity index PI."

up to perhaps $\frac{1}{2}$ inch across, can be handled with practical success provided the exponents m and n are known. As may be expected these exponents vary within broader ranges than in strictly granular reservoirs. Common ranges are from 2.1 to 2.6 for m, and from 2.0 to 1.5 for n, as the size varies from pinpoint to large.

(b) The evaluation of Type I reservoir volumes with widely scattered solution voids of very large dimensions is more difficult and less precise. The volumes exhibit very sharp and extensive discontinuities between the matrix and the voids, more or less in the manner of a giant Swiss cheese. Strictly speaking, the relationships of Section IIIA no longer apply to the bulk reservoir volumes. (They do apply to the unproductive matrix blocks.)

The invasion process is somewhat reminiscent of that described for Case C. The drilling mud moves bodily and swiftly into any voids and interconnecting channels communicating with the borehole, but the matrix imbibes mud filtrate at an extremely slow rate.

Well logs offer only limited assistance in the evaluation of such reservoirs. Use of a neutron log and an acoustic log, or a neutron log and a microlaterolog, does permit approximating the value of the secondary porosity. The neutron log yields the total porosity. The acoustic log yields the porosity of the matrix directly, since sound waves may travel easily and quickly either without encountering solution voids, or by skirting around those few present.

Estimation of the water saturation S_w almost requires that the oil-water contact be observable. Then S_w is approximated through equation (8): $I = R_t/R_o = S_w^{-n}$, where R_t and R_o are the values read off the R_t log above and below the contact, respectively. An arbitrary, low saturation exponent is selected, say $n = 1.4$. The method can only give very approximate results since equation (8) strictly speaking does not apply, for reasons stated. Also, it predicates constancy of the pore structure characteristics above and below the contact, which is too much to hope for.

Subcase D3. Secondary Porosity Due to Fractures

The evaluation through logs follows essentially the same reasoning as that for Subcase D2. The neutron log and either the acoustic log or a microlaterolog are run to obtain an approximation of the pore space contributed by the fracture system. The acoustic log and microlaterolog may detect fractures crossing the borehole.

Interpretation of the R_t log usually can be qualitative or comparative at best. At equal frequency of the fracture system, R_t will be higher in oil-bearing fractures than in water-bearing ones.

Carbonate Reservoirs Drilled with Oil-Base Muds and Air or Gas

A. Wells are drilled with oil-base mud to core a prospective reservoir under the best conditions possible, or to protect a water-sensitive reservoir from extensive damage. Coring with oil-base mud preserves intact the interstitial water

saturation in cores well above the transition zone. In the transition zone, oil filtrate may displace some of the water.

Logs which can be run without an electrical contact between the devices and the reservoir must be used, meaning gamma-ray log, induction log, and one or more non-electrical $F-\phi$ logs, namely neutron, acoustic and density.

In granular (and preferentially water-wet) reservoirs, the induction log yields R_t outright above the transition zone, but should require some correction in and below that zone. In reservoirs with fractures or solution voids, intrusion of the mud in the fractures or voids similarly does not alter the induction log in the oil or gas bearing parts, but may increase the log readings slightly in the water-bearing portion. Thus, log detection of oil-water contacts may be a little more difficult than would normally be the case.

B. In wells drilled with air or gas, only logs requiring no electric contact with the reservoir, or a liquid coupling with it, can be used. Thus, the logging program is limited strictly to gamma-ray log, induction log, neutron and density log.

IIID. LIMITATIONS OF LOG ANALYSIS DUE TO HETEROGENEITY OF CARBONATE RESERVOIRS

The time is now almost past due for considering in a general way the effects of extreme rock heterogeneity, and in passing, formation dip, on well logs.

Homogeneity and Isotropy

Of course, strictly speaking, all formations are heterogeneous to some extent. Even so-called homogeneous sands and shales do not preserve the same properties very far in any given direction. It is well to recall in fact that their properties such as resistivity, velocity, permeability, etc. have different values along a bedding plane than perpendicularly to it. Such anisotropy results from the fact that a number of the constituent particles of sands and shales possess flat or elongated shapes, thus tend to come to rest along the stratification surfaces. For certain applications of log analysis, it is indeed important to know that homogeneous sediments *are* anisotropic, and that, for instance, focused R_t and microresistivity measurements involve the longitudinal resistivity of rocks, while acoustic measurements involve their transversal velocity.

The heterogeneities of concern here however are not those observed from grain to grain, or pore to pore, or one stratification plane to another, but the macroscopic and megascopic heterogeneities corresponding to major changes in rock type and pore structure, or due to dip.

Volumes and Intervals. Two postulates of Log Analysis

It has been shown that logging devices are macroscopic tools, each involving at any given depth, a rock volume the size and shape of which are determined by its type and spacing, the petrophysical properties of the volume, and the effect of invasion, if any, on its response. In homogeneous formations with low to

moderate dip, the volumes are more or less of revolution around the axes of the respective devices, except for devices using pad arrangements (microresistivity and density). Figure 22 shows, more or less in proportion, the rough outlines of the volumes involved by the two R_t logs and four $F-\phi$ devices previously discussed.

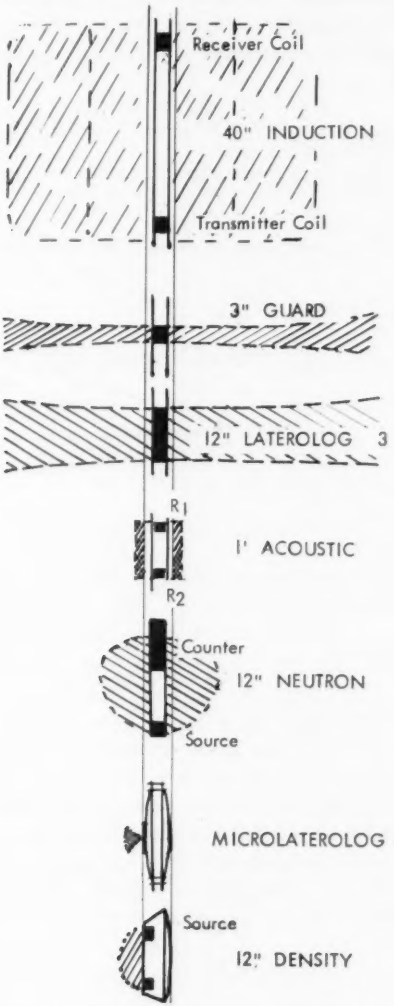


FIG. 22. Volumes investigated by various logging devices.

Log measurements may involve properties of *volumes*, but this could not be deduced from merely looking at a log. The representation which a log or curve gives of a property is strictly a one-dimensional plot of the apparent value of that property vs depth. On the basis of such plots, a reservoir under study is divided in depth *intervals*, and two postulates, without which in fact the log analysis could not be completed, are simultaneously made for each true property value in each interval analyzed:

1. The value applies to a horizontal slice of the reservoir having the same thickness as the interval.

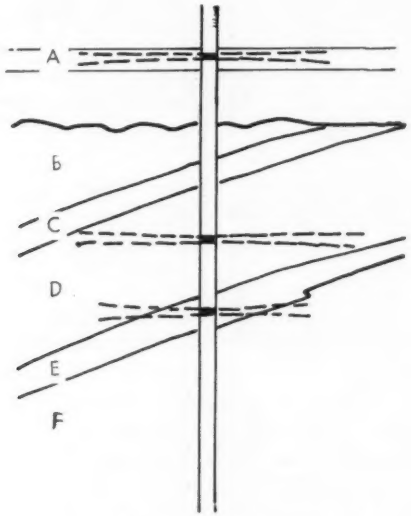


FIG. 23A. Effect of dip and thickness.

2. The value remains constant within the slice at least to the radius effectively investigated by the device with the deepest "reach," i.e. normally the R_t device.

The first postulate stems from the necessity of referring log responses to depths along a vertical (or nearly vertical) axis. It predicates that the division of the *log* in intervals, made on the basis of log responses, results in a valid division of the *reservoir* in horizontal homogeneous volumes. Its acceptance will result in a faulty analysis in two cases.

The first case is where the various layers of the reservoir are not horizontal and are too thin for the volumes investigated by the log to be wholly included therein. In Figure 23A, the first postulate is verified for the thick layers D and F, even though they show an appreciable dip. Layers C and E are so thin that

the laterolog device cannot help but radiate its current disc partly outside their borders. Layer A above the unconformity is thin also but happens to be horizontal, so that devices with still thinner spacings can reflect its properties.

The second case, most frequently encountered in carbonate reservoirs, particularly those with solution porosity, is that where the properties vary laterally, without any definite relation to whatever stratification the reservoir may possess. Consideration of this case, illustrated in Figure 23B, brings the second postulate into play.

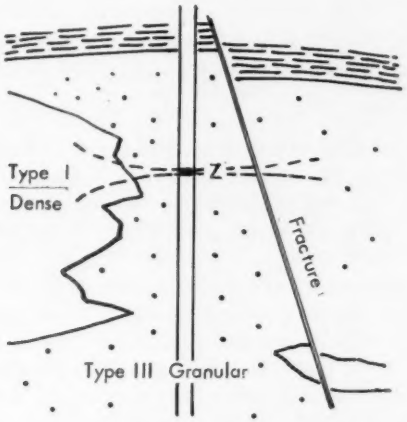


FIG. 23B. Heterogeneity.

This postulate is unavoidable if the log analysis relationships are to be used at all. By definition they are valid only in homogeneous volumes possessing constancy of PPD and petrophysical characteristics ϕ, F, m and n, V, etc. and of interstitial water resistivity R_w. Therefore, their application requires that all these properties keep the same values in the volumes investigated by the R_t and $F-\phi$ devices.

Figure 23B shows a situation where the second postulate is not valid. At depth Z the laterolog current disc encounters a fairly homogeneous, coarse-grained granular pore structure in the immediate vicinity of the borehole, a Type I, dense crystalline rock to the left, and portion of a fracture to the right. The $F-\phi$ log mainly sees the granular structure. Fortunately, such conditions generally result in marked, detectable anticorrelations among the various logs used.[31] There is normally no point in calculating the water saturation in intervals

[31] Of course, the log user must satisfy himself that he is not dealing merely with geometrical effects or other oddities caused by insufficient vertical resolution characteristics of one or more of the logs used. In this and other respects, it is highly desirable to run *all* the logs in a reservoir at a depth scale of 10 inches per 100 ft, or preferably 25 inches per 100 ft.

showing this effect. Figure 9 seemingly contains some such intervals (e.g. 3,573–3,575, 3,579–3,581, 3,594–3,597, 3,605–3,606.3 ft etc.).

The above observation should not be taken to mean that all intervals which show good correlations among the various logs will yield reliable results when analyzed. The readings of the different logs may still correspond to different pore structures or pore size distributions. After all, the possibility, not to say the probability, of such radial changes is one of the basic reasons for evaluating carbonate reservoirs on as broad and complete statistical basis as possible, whatever the specific technique used.

PART IV. WELL LOGGING AND LOG ANALYSIS IN AN INTEGRATED EVALUATION PROGRAM FOR A CARBONATE RESERVOIR

IVA. CONTRIBUTION OF WELL LOGS TO CARBONATE RESERVOIR EVALUATION

From all that has transpired in this brief review, and from experience, the following conclusions appear justified.

A. Modern well logs properly selected, run and interpreted, can play an important, often decisive role in the qualitative and volumetric evaluation of carbonate reservoirs, and in the task of completing individual wells therein. In their present but undoubtedly not ultimate stage of development, they are in fact generally capable of far greater achievements in such reservoirs than is commonly thought possible or demanded of them.

B. Such achievements however can be attained only on three conditions:

1. The logging program must have been planned for the reservoir (or reservoirs) to be penetrated, and for the type of drilling fluid used. Far better still, whenever possible, both drilling and formation evaluation programs should be planned together and ahead of time, and their various parts executed *in time* to render all the benefits expected of them while drilling and evaluating the reservoir(s). This requirement, of course, is not peculiar to carbonate reservoirs.

2. The analysis of the logs run in each well must be made in the light of all the other data obtained by logging time, such as drilling time log, mud log, drill stem tests, and most important of all perhaps, microscopic and macroscopic examinations of rotary cuttings or cores.[22]

3. The log interpretation must be made with a basic understanding of the effect of the double heterogeneity of pore structure and fluid distribution upon the application of the log analysis relationships and the conditions of use of logging devices.

IVB. INTEGRATION OF WELL LOGS IN VOLUMETRIC EVALUATION PROGRAM FOR A CARBONATE RESERVOIR

Looking at the problem of evaluating carbonate reservoirs from a still higher plane, certain general conclusions or guiding thoughts are in order:

[22] In return, the logs, when so interpreted, can help immeasurably in the interpretation and reconciliation of these other data. At the very least, they constitute a natural rallying and coordination center for these data, because of their continuous character and normally sharp delineation of the various formations penetrated.

1. In such reservoirs particularly, there is no perfect evaluation technique and each technique has its own contribution to make.

2. In each well, the quantitative evaluation techniques should be selected and used according to the pore structures that have been encountered. There can be no escape from this rule, nor from the necessity for detailed, accurate observation of said pore structures.

3. As soon as a reservoir has been discovered preparation should be made, at least on a tentative basis, for an integrated evaluation program, including drilling mud specifications, of course.

4. The integrated program should definitely include the provision for treating some future wells as *key wells* in which diamond cores will be secured and evaluated in terms of rock type, pore structure, porosity, permeability, residual fluids, and quite possibly electrical exponents m and n. Core plugs will be submitted to capillary pressure tests for pore size distribution and irreducible water saturation studies. All logs likely to be of assistance should at least be considered if not actually run. This normally means only one R_t log (through avoiding, if possible, the use of muds yielding R_{mf}/R_w ratios between 5 and 10), teamed with two or more $F-\phi$ logs.

5. From a study of all the key well data, the most effective and economical program for *development wells* may then be determined in function of the pore structures. One would rely entirely upon the lithological description and logs to reveal the existing conditions.

CONCLUSION

In final conclusion, the volumetric evaluation of a carbonate reservoir is most likely to require more time, effort and money, and doubtless greater cooperation among all parties concerned, than that of a sandstone reservoir of comparable size and merit. Be that as it may, a comprehensive, authoritative evaluation in either type of reservoir is becoming more and more in fact what it has always ideally been in principle, namely, the indispensable and logical culmination of all previous exploration and drilling activities, and the equally needed and best guide for most efficient, economical well completions and reservoir exploitation.

ACKNOWLEDGMENTS

The writer feels deeply indebted, and wishes it were possible for him personally to express his gratitude, to the authors of the papers which he has cited as references and of many others not listed, and to countless oil men and service company men with whom he has discussed formation evaluation problems over the years. May this serve instead.

He is also most grateful to those persons more directly connected with the writing and final editing of the paper: Dr. Hamilton Johnson of Tulane University, without whose encouragement the paper would not have been written; Mr. T. H. Braun of The Superior Oil Company for his assistance in the preparation of the preprints; Mr. A. A. Perebinossoff of Mobil International Oil Company for

his thorough reviews and benevolent suggestions and criticisms, which helped bring the paper to its present form. Warm thanks are also expressed to the oil companies who contributed actual examples of logs and related data.

Grateful acknowledgment is made of the permission granted by the Fifth World Petroleum Congress to reproduce Figure 3; permission granted by the Society of Petroleum Engineers of AIME to reproduce Table I and Figures 6 and 20; and of permission granted by the American Association of Petroleum Geologists to reproduce Figures 10 and 13. Thanks are also due Schlumberger Well Surveying Corporation and Seismograph Service Corporation for the use of portions of copyrighted charts in Figures 17 and 18.

REFERENCES

PART I

Archie, G. E., 1949, Introduction to petrophysics of reservoir rocks: AAPG, v. 35, n. 5.

——— 1951, Classification of carbonate reservoir rocks and petrophysical considerations: AAPG, v. 36, n. 2.

Atkinson, Burton, and Johnston, David, 1948, Core analysis of fractured dolomite in the Permian Basin: Transactions AIME 1949, 179, 128.

Brown, Harry W., 1950, Capillary pressure investigations: Transactions AIME 1951, 192, 67.

Buckley, S. E., and Leverett, M. C., 1941, Mechanism of fluid displacement in sands: Transactions AIME 1942, 146, 107.

Bulnes, A. C., 1945, An application of statistical methods to core analysis of dolomitic limestone: Transactions AIME 1946, 165, 223.

——— and Fitting, R. U., 1944, An introductory discussion of the reservoir performance of limestone formations: Transactions AIME 1945, 160, 179.

Chueca, A., 1959, Répartition des caractéristiques et facteurs influençant la récupération finale dans un réservoir carbonaté hétérogène: Fifth World Petroleum Congress, New York, Section II, Paper n. 19.

Craze, R. C., 1950, Performance of limestone reservoirs: Transactions AIME 1950, 189, 287.

Hassler, G. L., Brunner, E., and Deahl, T. G., 1942, The role of capillarity in oil production: Transactions AIME 1944, 155, 155.

Hohlt, Richard B., 1948, The nature and origin of limestone porosity: Quarterly of the Colorado School of Mines, v. 43, n. 4.

Houpeurt, André, 1949, Action des forces superficielles sur l'équilibre et le mouvement des hydrocarbures dans les roches magasins; Revue de l'Institut Français du Pétrole, v. 4.

——— 1952, Réflexions sur l'état d'équilibre des gisements vierges et sur les conditions mécaniques de la migration du pétrole: Paper given at Taormina, Sicily, April 1952: IRES—Palermo.

Hubbert, M. King, 1952, Entrapment of petroleum under hydrodynamic conditions: AAPG, v. 37, n. 8.

Law, Jan, 1943, A statistical approach to the interstitial heterogeneity of sand reservoirs: Transactions AIME 1944, 155, 202.

Leverett, M. C., 1940, Capillary behavior in porous solids: Transactions AIME 1941, 142, 152.

Livingston, H. K., 1942, Surface energy relationships in petroleum reservoirs: Transactions AIME 1943, 151, 147.

Muskat, Morris, 1948, Calculation of initial fluid distributions in oil reservoirs: Transactions AIME 1949, 179, 199.

——— 1949, Physical principles of oil production: The McGraw-Hill Book Company, Inc.

1958 Summary of operations, oil and gas fields: Geological Survey Division, State of Michigan.

Purcell, W. R., 1948, Capillary pressures. Their measurement using mercury and the calculation of permeability therefrom: Transactions AIME 1949, 186, 39.

Rockwood, S. H., Lair, G. H., and Langford, B. J., 1956, Reservoir volumetric parameters defined by capillary pressure studies: Transactions AIME 1957, 210, 252.

Rose, W., and Bruce, W. A., 1949, Evaluation of capillary character in petroleum reservoir rock: Transactions AIME 1949, 186, 127.

Russell, William L., 1951, Tilted fluid contacts: Principles of Petroleum Geology, The McGraw-Hill Book Co., Inc.

——— 1954, Tilted fluid contacts in Mid-Continent regions: AAPG, v. 40, n. 11.

Weaver, A. G. T., 1957, Carbonate reservoir evaluation based on mercury injection data, Western Canada: Canadian Well Logging Society Symposium.

Wentworth, Chester K., 1922, A scale of grade and class terms for clastic sediments: Journal of Geology, v. 30, n. 5, p. 377–392.

Winn, R. H., 1957, Log interpretation in heterogeneous carbonate reservoirs: Transactions AIME 1957, 210, 268.

Yuster, S. T., 1952, Some theoretical considerations of tilted water tables: Transactions AIME 1953, 198, 149.

PART II

American Petroleum Institute, 1959, Recommended practice for core analysis procedure: API RP 40.

Young, J. W., McLatchie, A. S., and Martin, T. H., 1950, The reporting of routine core analyses for maximum utility: The Petroleum Engineer.

PART III

Alger, R. P., 1957, Logging trends in carbonate rocks: The Mines Magazine.

API Bulletin D6, July 1955, Selection and evaluation of well completion methods.

Archie, G. E., 1941, The electrical resistivity log as an aid in determining some reservoir characteristics: Transactions AIME, 1942, 146, 54.

Bordat, Louis G., 1959, Vers une solution possible du calcul du volume des fissures des argiles silicifiees du Gabon au moyen des logs electriques: Bulletin de l'Association Francaise des Techniciens du Petrole, n. 135.

Bush, R. E., and Mardock, E. S., 1950, The quantitative application of radioactivity logs: Transactions AIME 1951, 192, 191.

Campbell, John L. P., and Wilson, John C., 1957, Density logging in the Gulf Coast area: Journal of Petroleum Technology, AIME.

Chombart, L. G., 1949, Factors involved in practical electric log analysis: Battenberg Press, University of Oklahoma, Norman Oklahoma.

——— 1956, General directives for the establishment of an exploration and evaluation program (in French): Chapter VIII, Reconnaissance et evaluation des formations, Société des Editions Techniq, Paris, France, July 27.

de Witte (Leendert), 1950, Resistivity and saturation distribution in invaded zones of porous formations: Oil & Gas Journal.

——— 1953, Resistivity logging in thin beds: Transactions AIME 1954, 201, 155.

——— 1957, Discussion of Reference, Dumanoir, J. L., Tixier, M. P., and Martin, Maurice, 1957, Interpretation of the induction-electrical log in fresh mud: Transactions AIME 1957, 210, 202: Transactions AIME 1957, 210, 379.

Doll, H. G., 1948, The S.P. Log: Theoretical analysis and principles of interpretation, Transactions AIME 1949, 179, 146.

——— 1949, Introduction to induction logging and application to logging of wells drilled with oil base mud: Transactions AIME 1949, 186, 148.

——— 1950, The microlog: a new electrical logging method for detailed determination of permeable beds: Transactions AIME 1950, 189, 155.

——— 1951, The laterolog: a new resistivity logging method with electrodes using an automatic focusing system: Transactions AIME 1951, 192, 305.
——— 1952, The microlaterolog: Transactions AIME 1953, 198, 17.
——— Dumanoir, J. L., and Martin, Maurice, 1959, Trends in electrical logging, presented at 29th annual meeting of the Society of Exploration Geophysicists, Los Angeles, November 9–12, 1959.
——— Legrand, J. C., and Stratton, E. F., 1947, True resistivity determinations from the electric log. Its application to log analysis: API Drilling and Production Practice.
Dumanoir, J. L., Tixier, M. P., and Martin, Maurice, 1957, Interpretation of the induction-electrical log in fresh mud: Transactions AIME 1957, 210, 202.
Dunlap, H. F., and Hawthorne, R. R., 1951, The calculation of water resistivities from chemical analyses: Transactions AIME 1952, 192, 373 (Technical Note 67).
Faul, H., and Tittle, C. W., 1951, Logging of drill holes by the neutron-gamma method and gamma ray scattering: Geophysics, v. 16, n. 2.
Gondouin, M., and Scala, C., 1957, Streaming potential and the S.P. log: Transactions AIME 1958, 213, 170.
——— Tixier, M. P., and Simard, G. L., 1956, An experimental study on the influence of the chemical composition of electrolytes on the S.P. curve: Transactions AIME 1957, 210, 58.
Guyod, Hubert, 1944, Electrical well logging, Oil Weekly.
Hardy, H. W., 1958, The continuous velocity logger. A geophysical-geological instrument: Third Annual Petroleum Conference on Well Logging Interpretations, McMurry College, Abilene, Texas.
Hill, H. J., and Anderson, A. F., 1958, Streaming potential phenomena in S.P. log interpretation: AIME Journal of Petroleum Technology, v. 216.
——— and Milburn, J. D., 1955, Effect of clay and water salinity on electrochemical behavior of reservoir rocks: Transactions AIME 1956, 207, 65.
Hutchinson, C. A., Jr., 1959, Reservoir inhomogeneity assessment and control (The Atlantic Lectures of the University of Texas, Part 11): The Petroleum Engineer.
Kohesh, F. P., 1951, Gamma ray logging: Oil & Gas Journal, July 26, 1951.
——— and Blizard, R. B., 1958, Geometrical factors in sonic logging: Geophysics, v. 24, n. 1.
Kunz, K. S., and Moran, J. H., 1958, Some effects of formation anisotropy on resistivity measurements in boreholes: Geophysics, v. 23, n. 4.
Martin, Maurice, and Dumanoir, J. L., 1956, How do the various logging devices compare when determining true resistivity: World Oil.
Owen, John E., and Greer, Walton J., 1951, The guard electrode logging system: Transactions AIME 1951, 192, 347.
Pirson, S. J., 1957, Formation evaluation by log interpretation; Part 4. Log interpretation in rocks with multiple porosity types; water or oil-wet: World Oil.
Russell, R. G., Morgan, F., and Muskat, Morris, 1946, Some experiments on the mobility of interstitial waters: Transactions AIME 1947, 170, 51.
Schlumberger, C. and M., and Leonardon, E. G., 1933, Some observations concerning electrical measurements in anisotropic media, and their interpretation: Transactions AIME 1934, 110, 159.
Schlumberger Well Surveying Corp., 1950, Interpretation handbook for resistivity logs: Document n. 4.
Seismograph Service Corporation, 1958, Continuous velocity logging. Porosity conversion charts: SSC Technical Bulletin n. 2A.
Shearin, J. M., Jr., and Latimer, J. R., Jr., 1954, Advantages of a coordinated formation evaluation program: AIME Transactions 1955.
Smith, H. D., and Blum, H. A., 1953, Microlaterolog vs microlog for formation factor calculations: Geophysics, v. 19, n. 2.
Stripling, A. A., 1958, Velocity log characteristics: Transactions AIME 1958, 213, 207.
Subcommittee on Review of API RP 33, 1959, Recommended practice for standard calibration and form for nuclear logs: American Petroleum Institute, New York.

Summers, G. C., and Broding, R. A., 1951, Continuous velocity logging: Geophysics, v. 17, n. 3.
Tittle, C. W., Faul, J., and Goodman, G., 1951, Neutron logging of drill holes. The neutron-neutron method: Geophysics, v. 16, n. 4.
Tittman, Jay, 1956, Radiation logging: Petroleum Engineering Conference, University of Kansas.
Tixier, M. P., 1949, Electric log analysis in the Rocky Mountains, The Oil and Gas Journal.
——— Alger, R. P., and Doh, C. A., 1958, Sonic logging: AIME Technical Paper 1115G, Houston.
——— Alger, R. P., and Tanguy, D. R., 1959, New developments in induction and sonic logging: 34th Annual Fall Meeting of SPE of AIME, Dallas.
Walstrom, J. E., 1950, Optimum use of various testing methods in exploratory wells: API Drilling and Production Practice, 79.
——— 1951, The quantitative aspects of electric log interpretation: Transactions AIME 1952, 195, 47.
——— and Wells, J. C., 1955, How to size up wildcat pay zones: Oil and Gas Journal, June 6.
Whiting, R. L., Guerrero, E. T., and Young, R. M., Electrical properties of limestone cores: The Oil and Gas Journal, July 27, 1953.
Winsaeur, W. O., Shearin, H. M., Masson, P. H., and Williams, M., 1951, Resistivity of brine-saturated sands in relation to pore geometry: AAPG v. 36, n. 2.
World Oil, "New logging technique measures density, porosity": December 1954.
Wyllie, M. R. J., 1948, A quantitative analysis of the electrochemical component of the S.P. curve: Transactions AIME 1949, 186, 17.
——— 1950, An investigation of the electrokinetic component of the self potential curve: Transactions AIME 1951, 192, 1.
——— 1957, The fundamentals of electric log interpretation, Second Edition: Academic Press, Inc., Publishers, New York.
——— and Gardner, G. H. F., 1958, The generalized Kozeny-Carman equation: World Oil.
——— Gregory, A. R., 1952, Formation factors of unconsolidated porous media: Influence of particle shape and effect of cementation: Transactions AIME 1953, 198, 103.
———, ——— and Gardner, L. W., 1955, Elastic waves velocities in heterogeneous and porous media: Geophysics, v. 21, no. 1.
———, ——— and Gardner, G. H. F., 1957, An experimental investigation of factors affecting elastic wave velocities in porous media: Geophysics, v. 22, n. 3.
——— and Rose, Walter D., 1949, Some theoretical considerations related to the quantitative evaluation of the physical characteristics of reservoir rock from electric log data: Transactions AIME 1950, 189, 105.
——— and Spangler, M. B., 1951, Application of electrical resistivity measurements to problem of fluid flow in porous media: AAPG v. 36, n. 2.

GEOPHYSICS, VOL. XXV, NO. 4 (AUGUST, 1960), PP. 854–882, 12 FIGS.

SUGGESTIONS FOR BETTER ELECTRIC LOG COMBINATIONS AND IMPROVED INTERPRETATIONS*

H. G. DOLL,† J. L. DUMANOIR,† AND MAURICE MARTIN‡

ABSTRACT

In modern electrical logging, several resistivity measuring devices are now available or are under development which cover a wide range of radial investigations. In order of increasing penetration, they include:

a) The Proximity Log (a new tool for recording formation resistivity close to the wall of the hole).

b) A new type of Laterolog having a shallow investigation and adapted for simultaneous recording with an Induction Log.

c) An Induction Log appropriate for moderate invasion (e.g., the present 5FF40).

d) A deep investigation Induction Log (e.g., the new 6FF40).

All these devices have a high vertical resolution, and their readings are practically unaffected by the mud column.

This paper deals essentially with the case of logging in fresh mud. A discussion is presented of the information which can be obtained on saturation, when combinations of respectively two, three, or four of the above listed devices are used.

The general case where nothing is known about the depth of invasion is first considered:

The combination of the Laterolog and deep investigation Induction Log, when compared with SP curve, permits visual recognition of most salt-water-bearing beds.

With the addition of the Proximity Log, and medium investigation Induction Log, the effect of invasion can be estimated and the distinction of practically all water-bearing and oil-bearing beds is made possible. The possible presence of a low resistivity zone beyond the invaded zone can be detected and accounted for. The ratio R_{xo}/R_t can be determined, from which an estimation of saturation can be made. The value of R_t can be furthermore derived, which gives another way of computing saturation if the formation factor can also be obtained, for example from the porosity given by a Sonic Log.

In these combinations the 16 inch normal can be used instead of the Laterolog, when bed resistivities are not too high.

In those regions where the depth of invasion is known from local experience, one or even two of the above devices can be omitted.

The advantage of a logarithmic resistivity scale for a convenient and rapid visual interpretation of the logs is explained.

Charts to be used in the above procedures are shown, and the discussion is illustrated with field examples.

LIST OF SYMBOLS

d = hole diameter
D_i = electrically equivalent diameter of the invaded zone
D_1 = inside diameter of transition zone
D_2 = outside diameter of transition zone
F = formation resistivity factor
G = geometrical factor for Induction Log
J = geometrical factor for Proximity Log or Laterolog
R_a = apparent resistivity

* Presented at the 29th Annual Meeting, Los Angeles, California. November 11, 1959. Manuscript received by the Editor February 15, 1960.

† Schlumberger Well Surveying Corporation, Ridgefield, Connecticut.

‡ Formerly with Schlumberger Well Surveying Corporation, Ridgefield, Connecticut, now with Geopetrole, Paris, France.

R_{an} = resistivity of "annulus" (zone of low resistivity between invaded zone and uncontaminated zone)
R_m = mud resistivity
R_{mc} = mud cake resistivity
R_{mf} = mud filtrate resistivity
R_o = resistivity of a formation 100 percent saturated with water of resistivity R_w
R_s = resistivity of formations adjacent to bed under study
R_t = true resistivity of uncontaminated zone
R_w = resistivity of formation water
R_{wa} = in shaly sands, apparent resistivity of interstitial water, corresponding to the equation PSP $= -K \log R_{mf}/R_{wa}$ where PSP is the Pseudo-Static SP
R_{xo} = resistivity of invaded zone close to the wall of the hole, where flushing has been maximum
S_w = water saturation of the uncontaminated zone
S_{xo} = water saturation of flushed zone
R_{PL} = resistivity measured with Proximity Log
R_{LLs} = resistivity measured with shallow investigation Laterolog, LLs
R_{ILm} = resistivity measured with medium Induction Log (e.g., the 5FF40)
R_{ILd} = resistivity measured with deep Induction Log (e.g., the 6FF40)
R_{SN} = resistivity measured with the 16 in. normal

INTRODUCTION

The primary purpose of this paper is to study, in the light of the number and nature of the electrical logs becoming available, what can be done under various conditions of invasion to achieve:

(a). Qualitative interpretation (i.e., differentiation between water-bearing and oil-bearing formations) and

(b). Quantitative interpretation (primarily the determination of R_t and R_{xo}/R_t for use in the evaluation of saturation).

The most important objectives are:

(1). To differentiate unequivocally between oil-bearing formations and deeply invaded water beds. This requires three suitably chosen resistivity logs.

(2). In oil-bearing formations, to detect and evaluate the effect of an "annulus,"[1] if present, and to arrive at a more accurate value of R_t. Since, in this case, the quantitative interpretation is concerned with the determination of four unknowns (R_t, R_{xo}, D_i, and the nature of the invaded zone), a complete solution is not possible with less than four ***appropriately chosen*** logging devices. There is, for example, little advantage in the addition of another log to the basic data if,

[1] A zone of low conductivity between the invaded and non-invaded zones of an oil sand. See Campbell and Martin (1955). References are listed at the end of the paper.

at the same time, one introduces additional variables (such as mud cake thickness and mud cake resistivity) which are still unknown and must be accounted for. In addition, the devices to be used must show an appropriate variety in the depth of investigation and the manner of investigation, in order that there will be good resolution in the evaluation of the desired parameters; i.e., so that there will be no indetermination in the answers found.

The discussion will relate essentially to electric logs, for the reason that they are, at least in the present state of logging technology, the only ones capable of solving the above problems.[2] It will further relate to certain focused logging devices, for which the measurements are unaffected, or little affected, by the presence of media other than the permeable beds under consideration (i.e., mud column, mud cake, or adjacent beds).

Porosity can be determined today by means of several different logging methods, such as the Sonic, Neutron, or Gamma-Gamma Logs, the Microlog or the Microlaterolog. The application of these logs to the determination of porosity has already been adequately described in the literature, and will not be repeated here. It will be admitted, however, that the porosity is generally determined, and is therefore available when it can be of help for the interpretation of the electric logs.

The paper is written with reference to cases where R_{xo} is greater than R_t. Generally speaking, this is the case where the muds are less saline than the formation water. It is for this case that the set of logs to be used in the discussion applies particularly well.

Four resistivity devices are considered, in addition to the SP log. They are:

(1) The standard Induction Log, the 5FF40, which will be referred to as the ILm (m for medium).

(2) A new Induction Log, known as the 6FF40, which has a depth of investigation twice as large as that of the 5FF40, and which will be referred to as the ILd (d for deep).

(3) A Laterolog having a comparatively shallow depth of investigation, referred to as the LLs (shallow investigation Laterolog).

(4) A focused device having a depth of investigation not more than one third that of the LLs, but which is deep enough that the response of the device is unaffected by mud cakes up to $\frac{3}{4}$ inch in thickness. These requirements are satisfied by the Proximity Log. Any other focused radial investigation device to be considered as the fourth member of this combination *must satisfy the requirements of investigation depth and immunity to mud cake effects.*

The charts to be presented in this paper could be extended to the case of R_t greater than R_{xo}. In fact, the same or similar devices could be used with about

[2] Mention should be made here, however, of the "chlorine log," which can, under favorable conditions, detect oil saturation existing in the vicinity of the hole.

the same results in salty mud, a requirement being that the devices not be sensitive to the effects of the conductive mud. This requirement is more severe for the Induction Logs; and for salty muds the existing ILm (i.e., the 5FF40) should be replaced, if possible, by other devices having about the same depth of investigation but less sensitive to the characteristics of the mud column (mud resistivity and hole diameter). Since mud cakes are generally thinner in salt muds, the requirement that the devices not be affected by mud cake is less severe as regards the microfocused devices and the unfocused microdevices (Microlog).

While the discussion is limited to the use of the four resistivity logs listed above, it must be kept in mind that the conclusions remain valid if the LLs is replaced by the 16 inch normal provided the short normal readings are not too much affected by the mud column and by the adjacent beds or can be corrected for these effects. These conditions are satisfied when the beds are thick and when their resistivity is not too large in comparison with that of the mud column (as in unconsolidated formations). In other cases, and in particular for thin beds in consolidated formations, the LLs is much to be preferred because the short normal would require substantial corrections, which are complicated to introduce, whereas the LLs readings can be used directly. Similarly, the Proximity Log can be replaced by the Microlaterolog or by any other short-range log if it is certain that the mud cake thickness is small enough so as not to affect the readings (less than $\frac{3}{8}$ inch for the Microlaterolog).

In order to concentrate the discussion on its primary objective, which is the determination of R_t and the possible influence of the invaded zone on the interpretation, it will be admitted that the permeable beds under consideration are thick enough so that no corrections for bed thickness are needed, or that the proper corrections have been made when desirable. This assumption is reasonable since the LLs and Proximity Log very seldom require corrections, and since the corrections for the Induction Logs are generally small and easy to make with the proper correction charts.

As far as interpretations are concerned, the ideal would be an Induction Log which always reads R_t directly; then everything would be very simple. But for this condition to be always satisfied without any doubt, an Induction Logging device with a very large depth of investigation would be required. Unfortunately there is not, in the present state of induction logging technique, such a device available which would not, at the same time, have several objectionable features, such as prohibitive length, making it unmanageable, and poor vertical resolution. Let us use the approximation $R_t = 0.8\ R_{IL}$ and agree to accept a possible error of ± 20 percent in R_t (that is, a possible error of ± 10 percent in S_w). Then, with this approximation, the 5FF40 (ILm), which has been the standard Induction Log for several years, gives R_t directly when the invasion diameter is less than about 50 inches.[3] With the same approximation, the 6FF40 (ILd) gives R_t directly for invasion diameters up to about 100 inches.[3]

[3] As will be seen in Figure 5.

The increased radial investigation of the ILd makes less frequent the necessity of corrections to the Induction Log reading. It often happens, too, that local experience or additional information available makes it certain that the Induction Log is reading R_t. This is the case, for example, in formations where the porosity and R_w are determined, and the measured value of resistivity clearly corresponds to 100 percent water saturation.

However, in regions of very deep invasion, or in regions where conditions are unknown, it becomes necessary to determine whether the invasion does or does not exceed the value above which the Induction Log requires correction. Such cases exist, and consequently the recording of additional resistivity curves is highly desirable, not only to resolve the uncertainty as to the depth of the invasion, but also, when necessary, to properly correct for the influence of the invaded zone. When these additional logs are available, the value of R_{xo}/R_t is also obtained and is a great help for the interpretation with respect to saturation in many cases, and in particular for shaly sands.

The primary invasion model for this study is one in which the bed consists of two homogeneous media of resistivity R_{xo} and R_t respectively, separated by a cylindrical boundary of diameter D_i. However, the effect of the invaded zone cannot always be described in terms of this simple no-transition-zone model. In the case of oil sands the possibility of an *annulus* of low resistivity between the invaded zone and uncontaminated zone must be considered. In case of water sands and low oil saturations, there is statistical and experimental evidence of another type of transition zone which corresponds approximately to a linear gradient of water salinity between flushed and uncontaminated zones. Although its existence is well recognized, this type of transition zone will only be touched on in the present paper.

In listing the unknowns to be solved in the logging problem, the existence in varying degree, or non-existence, of the annulus was considered as a single variable, since what counts is the composite effect of its conductivity and thickness. The annulus can be particularly vicious in its effect on interpretations if R_{mf}/R_w is large and R_t is equal to or not much smaller than R_{xo}.

The text which follows will begin with a discussion of the characteristics of the above-listed four logging tools.

This will be followed by a discussion of what can be done, in fresh muds, with appropriately chosen combinations of two, three, or four of the above-listed four devices. The theoretical discussion of the interpretation with three or more logs will be based on interpretation charts whereby values of R_{xo}/R_t, D_i and R_t can be determined under the conditions of no transition zone or of the presence of an annulus.

In a section on practical considerations the advantages of log presentation using a logarithmic scale will be explained. Use of a logarithmic scale facilitates the application of a ratio rule, which will be described, whereby most water-bearing beds may be identified from a comparison of the SP, the LLs and the ILd.

Field examples will be given.

DESCRIPTION OF THE FOUR RESISTIVITY DEVICES

For simplicity in describing the performance of the resistivity tools, the assumption of no transition zone will be made.

(1) *Proximity Log*

With this log, an improved focusing system of electrodes is applied to the wall of the hole by means of a pad. The characteristics of this tool were determined in an electrolytic test tank in the laboratory by means of measurements made on full-scale models and actual field sondes.

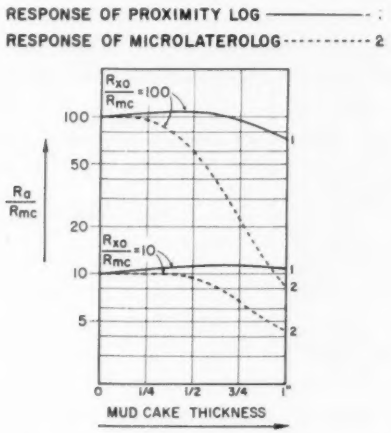


FIG. 1. Effect of mud cake thickness on response of Proximity Log. (Laboratory Data)

(a) *Mud Cake Effect.*—For the determination of the mud cake effect, the invaded zone was far extended, beyond the radius of investigation of the device (in practice, up to the limits of the tank). Some typical results of this investigation are shown in Figure 1, where the mud cake thickness is plotted in abscissae, and the ratios of the apparent resistivity R_a to the mud cake resistivity R_{mc} are plotted in ordinates. It is seen that the tool reads practically R_{xo} when the mud cake thickness does not exceed $\frac{3}{4}$ inch, even for high values of the ratio R_{xo}/R_{mc}. (The corresponding curves for the standard Microlaterolog are also traced on the figure for comparison.)

Since there appear to be no published data on the characteristics of types of microfocused devices, other than the Microlaterolog, we are unable to reproduce them here for comparison. Microfocused devices in current field use have their widest applications in salt muds, where mud cakes are generally very thin, and where mud cake thickness is not a problem. In fresh muds, however, mud cakes are not necessarily thin and their presence may necessitate the correction

of the readings of conventional microfocused devices. A deviation of 10 percent of the reading from the true value is considered serious enough here to require correction.

Inasmuch as mud cakes thicker than $\frac{3}{4}$ inch are extremely rare, it can be said that the Proximity Log, as a matter of fact, is unaffected by mud cakes in general. This is true for any type of formations (soft or hard).

(b) *Radial Investigation.*—The radial investigation of the tool was studied in the test tank for a wide range of values of D_i, R_{xo}, and R_t.

By processing the laboratory data, it was found, at least for R_{xo} greater than

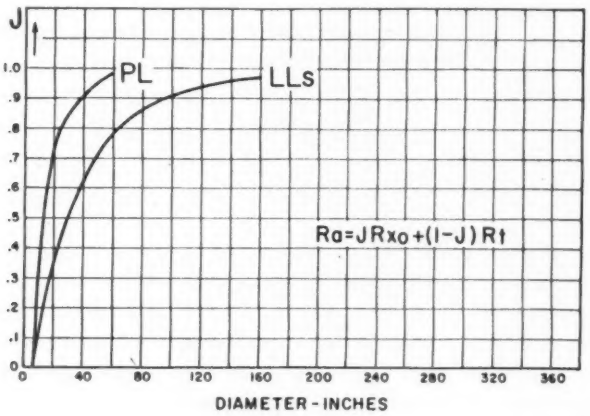


FIG. 2. Approximate radial investigation characteristics of Proximity Log (PL) and shallow Laterolog (LLs). Proximity Log data are from test tank measurements, $d=8$ inches. LLs data are from IBM computations for thick beds.

R_t, that the reading R_a can be expressed approximately by an equation such as:

$$R_a = JR_{xo} + (1 - J)R_t \tag{1}$$

where J depends on the diameter of invasion only. The factor J, by definition, is the geometrical factor of the Proximity Log, comparable to that used for the computation of the Induction Log.[4]

Figure 2 shows, for a hole diameter of 8 inches, the values of J as a function of D_i. It is seen that the geometrical factor is equal to 0.90 for $D_i=40$ inches.

[4] With the Proximity Log, the current is forced into the formation as a more or less horizontal beam. The measured value is the sum of the series resistances offered to this current, first by the invaded zone, then by the non-invaded zone. With the Induction Log, the current flows along coaxial, horizontal circular loops, and the measured value is the sum of the conductances (parallel resistances) of the two media. The formula expressing the Proximity Log reading accordingly involves "resistivities" whereas that expressing the Induction Log reading involves "conductivities."

This means that 90 percent of the geometrical factor is comprised within a distance of 16 inches from the wall.

(c) *The Vertical Resolution.*—Resolution of the Proximity Log is about 6 inches; this is an advantage over the Microlaterolog, which is sometimes sensitive to small accidents of no practical significance, such as "oyster shells" on the wall of the hole. Corrections for the effect of adjacent beds on the readings of the Proximity Log are unnecessary for bed thicknesses greater than 1 ft.

The Proximity Log has been used in the field for several months. The laboratory data have been well confirmed by field experience in general. An example of a Proximity Log recording is given in Figure 10.

(2) *Shallow Investigation Laterolog*

Whereas the standard Laterolog is designed for the measurement of R_t in salt mud, the shallow investigation Laterolog (LLs) is intended to be an auxiliary tool

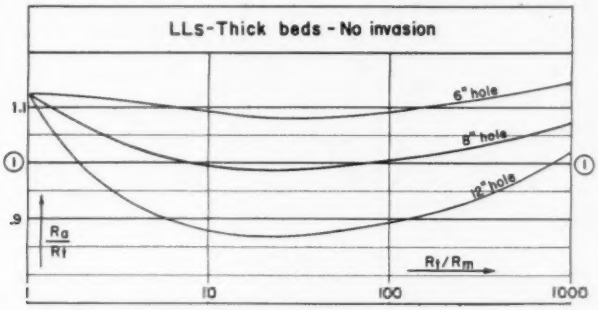


FIG. 3. Effect of mud column on response of shallow Laterolog, based on IBM computations.

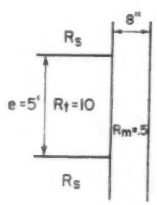
to the Induction Log in fresh mud. Its radius of penetration has been reduced, compared with the standard Laterolog, so that its readings are more affected by R_{xo} and D_i than they are by R_t. In addition, the LLs has better vertical resolution than the standard Laterolog.

(a) *Borehole Effect.*—The effect of the borehole has been studied by computations on IBM machines, assuming the formation to be infinitely thick, homogeneous, and non-invaded, and taking into account the actual geometry of the device. The essential results are presented in Figure 3 where the ratio of the reading R_a of the tool to the true resistivity R_t is plotted vs R_t/R_m. Curves are shown for hole diameters ranging from 6 inches to 12 inches. The instrument has been calibrated so that R_a is practically equal to R_t under the conditions most frequently encountered; namely, for hole diameters of approximately 8 inches and for values of R_t/R_m ranging from 3 to 300. For $d=6$ inches or 12 inches, the readings are respectively 10 percent higher or 10 percent lower, and can easily be corrected.

(b) *Radial Investigation.*—In the Laterolog, a horizontal sheet of current flows across the formations. Just as for the Proximity Log, therefore, it is possible to express R_a through an equation such as (1). Figure 2 gives the value of the geometrical factor of the LLs in terms of D_i. This curve, derived from analysis of the IBM computations, is approximate and applicable only for the case of $R_t < 2R_{xo}$.

With the LLs, 90 percent of the geometrical factor is attained when $D_i = 95$ inches; i.e., at a distance of about 43 inches from the wall of the hole. This compares with 16 inches found for the Proximity Log. It can be said, accordingly, that the depth of investigation of the LLs is roughly three times that of the Proximity Log.

(c) *Vertical Resolution.*—The response of the LLs for a 5-ft bed of 10 ohm-m resistivity, as determined experimentally in the laboratory on a resistor network analog, is shown in Figure 4. The tabulated values are the apparent resistiv-



LLs vs. 16" NORMAL

R_s	R_a	
	SN	LLs
.5	6	8.5
5	9	9.5
50	18	11.5
500	32	12.5

FIG. 4. Comparison of readings of LLs and 16 inch normal (right) for thin-bed case sketched at left (laboratory data).

ities for several values of R_s, adjacent formation resistivity. The corresponding readings of the 16 inch normal are also given for comparison. When R_s ranges between .5 and 500, the LLs reads between 8.5 and 12.5, relatively close to the true value 10, whereas the short normal varies from 6 to 32. The effect of adjacent beds on the readings of the LLs can generally be ignored if the bed thickness is greater than 5 ft.

(3) *Medium Investigation Induction Log (ILm)*

The present 5FF40 (Dumanoir et al, 1957) is a good example of what the ILm may be. Whatever may be the physical characteristics of future versions of the ILm, their responses will always be close to that of the 5FF40, and any design change will be prompted mostly for engineering reasons.

The ILm is practically unaffected by the fresh mud column if the tool is run with fixed stand-off devices. The effect of adjacent formations is practically negligible for bed thicknesses above 5 to 6 ft, under normal conditions. The radial investigation is illustrated in Figure 5, which gives the (integrated radial) geo-

metrical factor; i.e., the value in terms of D_i of a factor G such that the apparent conductivity, $1/R_a$, for an infinitely thick bed is:

$$\frac{1}{R_a} = G\frac{1}{R_{xo}} + (1 - G)\frac{1}{R_t}. \tag{2}$$

(4) *Deep Investigation Induction Log (ILd)*

Several induction logging devices are under study at present, in order to obtain the deepest possible penetration without impairing the vertical resolution.

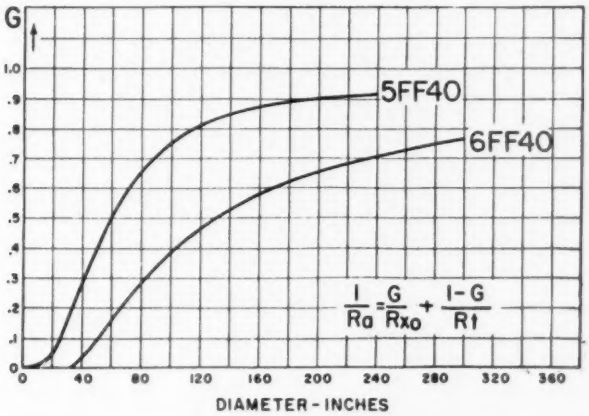


FIG. 5 Radial investigation characteristics of 5FF40 and 6FF40 Induction Logging sondes. Data are taken from computations for thick beds, skin effect neglected.

One tool has already been developed and introduced into field practice a few months ago. This tool, referred to as the 6FF40 (Tixier et al, 1960) has a radius of investigation about twice as large as that of the 5FF40—yet it shows about as much detail. The effects of adjacent formations with the 5FF40 and 5FF40 are comparable for moderate resistivity contrasts and for a large range of bed thicknesses. The radial investigation characteristic of the 6FF40 is shown in Figure 5.

It is likely that the other types of deep investigation induction sondes now under development will have about the same radial characteristics as the 6FF40. The improvement will be essentially in better vertical resolution.

It is convenient, in describing the response of Induction Logging tools, to consider the signal as being the sum of two terms: the first term is computed on the basis of the geometrical factor only; the second term is the skin effect, which is generally smaller but is more complex to handle mathematically.[5] The skin effect term increases with formation conductivity, and with the radius of pene-

[5] See Appendix of Dumanoir et al (1957).

tration of the measuring device. This term has been neglected in computing the Induction Log values which appear in existing charts. The equipment has been designed in such a way that the log readings do not need correction for skin effect except in the case of beds which are highly conductive and deeply invaded, or too thin. Charts appropriate for these less usual cases are presently being established.

Great efforts are being made to design combination sondes, such that several devices can be recorded simultaneously and the number of runs thereby reduced to a minimum. The ideal would be of course, to devise such elaborate tools that all desirable curves, including the four resistivity logs, the SP, Microlog, Microcaliper Log, and a porosity log (Sonic, for example) could be recorded in only two runs.[6]

INTERPRETATION WITH AN INDUCTION LOG AND A POROSITY DETERMINATION

A simplified interpretation procedure has been proposed in which the value of R_{IL} at various levels is plotted on a special grid vs the corresponding porosities or, equivalently, vs the Sonic Log transit times. If it is admitted that the Induction Log reads R_t directly, the corresponding saturations can be derived from the positions of the plotted points on the grid.

Since the method has been treated in detail by Tixier et al (1960), it is not discussed fully here.

The main limitation of the procedure is that when the invasion is too deep the Induction Log reads higher than R_t, so that an erroneous conclusion is then possible. Fortunately, with the deep Induction Log (ILd), this should not happen unless the invasion diameter is larger than 100 inches.[7] The trouble is that in the absence of other information (other resistivity logs) there may be no warning if by any chance the invasion is too deep.

It is to eliminate this uncertainty that methods using additional resistivity logs as well as the porosity determinations are proposed hereafter.

In the case of shaly sands, interpretation is generally more accurate if R_{xo}/R_t, rather than R_t, is used in combination with the SP. The value of R_{xo} can be obtained from the Microlog, if available, provided that R_{xo}/R_{mc} is smaller than 20.

INTERPRETATION WITH AN INDUCTION LOG, LLS, AND THE SP

In this and the following sections, it will be admitted that a permeable bed comprises a homogeneous invaded zone of resistivity R_{xo}, extending to a diameter D_i, beyond which the uncontaminated zone, also homogeneous, has the resistivity R_t. This case is referred to on the charts as "no transition zone, no annulus," and the corresponding charts are so designated. The differences resulting

[6] Field tests which include all the above listed tools, but recorded in more than two runs, have been conveniently designated by the colloquial expression of "Grand Slam" tests. This term will be used again in the present paper.

[7] As previously stated, this amounts to taking $R_t \cong 0.8\, R_{ILd}$ and accepting a possible error of ± 20 percent in R_t or a possible error of ± 10 percent in S_w.

from either a transition zone or an annulus will be discussed later.

When only one Induction Log is used, in combination with the LLs and the SP, it will be assumed that it is the ILd. If the ILm were substituted, the conclusions would be essentially the same, except that some numerical figures would be changed.

In the general case where nothing is known about the depth of invasion, a complete interpretation requires additional information, essentially to estimate R_{xo}, and the use of a chart such as that of Figure 6.[8]

When the chart of Figure 6 is entered in ordinates with the ratio R_{LLs}/R_{ILd} and in abscissae with the ratio R_{xo}/R_{LLs}, a point M can be determined, and the values of R_{xo}/R_t and D_i can be estimated by interpolation between the solid curves (R_{xo}/R_t) and the dashed curves (D_i). (The dash-dot curves of Figure 6 correspond to the ratio R_{LLs}/R_{ILm}. They can be used to enter the chart, instead of the ordinates, when the ILm (5FF40) is used instead of the ILd (6FF40).)

To be rigorous, allowance should be made for the possible effect on the interpretation of a small percentage of error in the log values. Each point plotted on an interpretation chart, such as Figure 6, should be thought of as surrounded by a small area representing the possible range of interpretational results within the uncertainty of the log determinations. The effect of an uncertainty of ± 5 percent in the ordinate and abscissa of point M in Figure 6 is shown by the cross-hatched rectangle surrounding the point. The rectangle corresponds to possible D_i values ranging from 42 inches to 60 inches and to R_{xo}/R_t values ranging from 10.5 to 12.5.

Use of inaccurate or poorly corrected logs will, of course, increase the area of uncertainty on the chart.

A good estimate of R_{xo}, generally accurate within ± 10 percent, can be obtained from the Microlog in those cases where R_{xo}/R_{mc} is not greater than 20.

If no Microlog is available, or if R_{xo}/R_{mc} is too large, an estimate of R_{xo} can be obtained from the porosity, if available, by use of the relation $R_{xo} = FR_{mf}/S_{xo}^2$. But in that case the value obtained for R_{xo} should be considered as a ***rough approximation***, often accurate only within ± 40 percent, because it accumulates all possible uncertainties: in the determination of porosity, in the determination of R_{mf}, in the estimation of residual oil saturation, in the possible influence of shale content in the formation, and in the validity of the relation between the porosity and the formation factor. Thus, if the R_{xo} value entered into Figure 6 is derived from the porosity value, only a very rough estimate of D_i will be obtained, and the only guarantee that the true D_i is sure to be less than 100 inches is that the estimated D_i be less than 40 inches (the chart shows a shift from 40 inches to

[8] The charts of Figures 6, 7 and 8 have been established assuming the beds to be homogeneous, isotropic, and infinitely thick (i.e., the log readings are unaffected by the adjacent beds). For all charts the hole diameter is assumed to be about 8 inches. For other diameters the chart would be somewhat different. Eventually charts for perhaps two or three diameters may have to be made available. The charts are to be extended at a later date to cover cases of R_{xo} less than R_t.

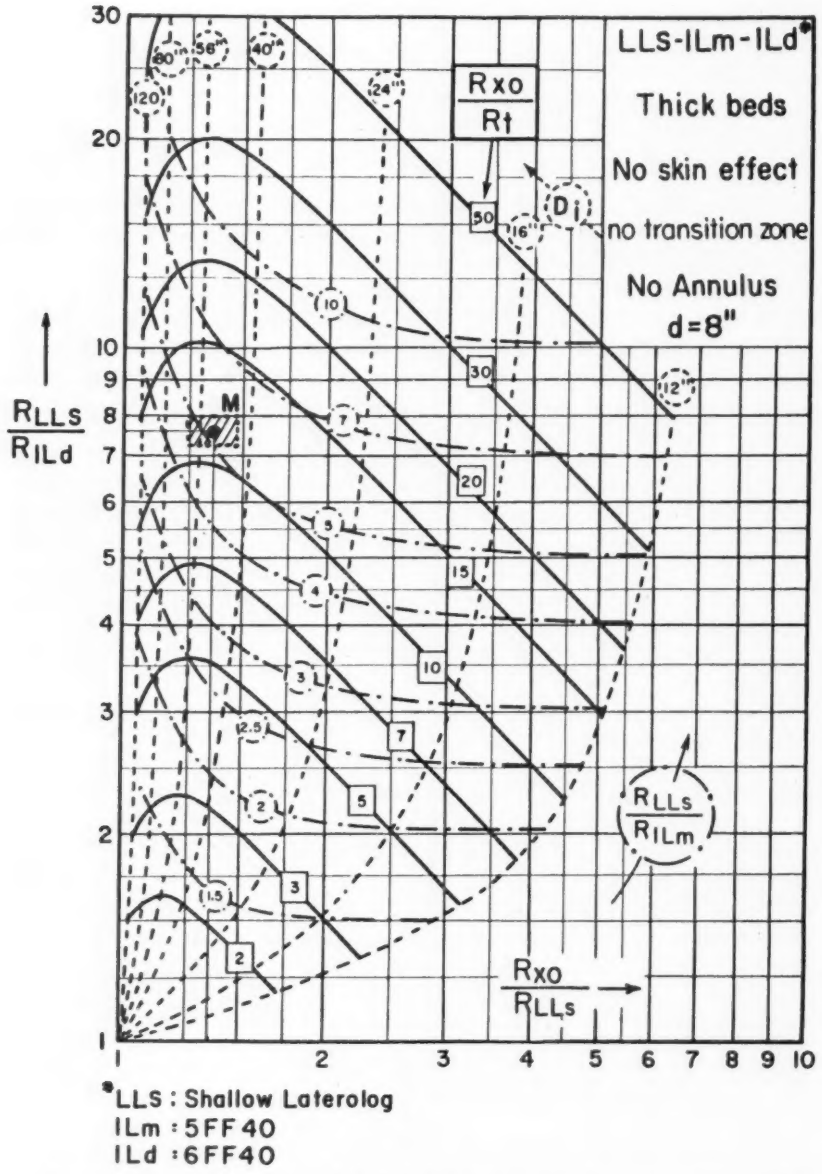


FIG. 6. Interpretation chart for conditions of thick beds, no transition zone and no annulus. The chart is entered with R_{LLs}/R_{ILd} (ordinates) and either R_{xo}/R_{LLs} (abscissae), or R_{LLs}/R_{ILm} (dash-dot curves). (The cross-hatched rectangle enclosing point M shows effect of ± 5 percent uncertainty in the plotted values.) Values of D_i are read on dashed curves, and values of R_{xo}/R_t on solid curves.

100 inches for D_i if R_{xo} is reduced by 40 percent, which corresponds to the uncertainty). If the estimated D_i is less than 40 inches R_t can be taken as equal to 0.8 $R_{ILd} \pm 20$ percent; otherwise R_t cannot be safely obtained without additional information.

There is however, in the case of water-bearing formations, a very important exception which can generally be identified without ambiguity for diameters of invasion up to 150 inches. This case, which is discussed in more detail later in the text, is based on the following relation:[9]

$$\frac{R_{xo}}{R_t} \cong 2 \frac{R_{LLs}}{R_{ILd}} \pm 30 \text{ percent} \tag{3}$$

which is valid as long as R_{xo}/R_t is larger than 5 (a condition frequently satisfied in water-bearing formations drilled with comparatively fresh muds), and as long as D_i is larger than 24 inches and smaller than 150 inches.

If the value of R_{xo}/R_t estimated from relation (3) is not appreciably smaller than R_{mf}/R_{wa}, as obtained from the SP, *the formation is bound to be water-bearing* and the invasion is between the prescribed limits, since any other condition would automatically have given a lower value for the estimated R_{xo}/R_t.[10]

In the case of D_i smaller than 24 inches, the estimated D_i, in the worst case (i.e., when based on a porosity-derived R_{xo}), will be smaller than 40 inches. As already noted, R_t will, for an estimated D_i less than 40 inches, always be equal to 0.8 $R_{ILd} \pm 20$ percent, and, with the help of an approximate value of R_{xo}, a comparison of R_{xo}/R_t with R_{mf}/R_{wa} is possible.

Thus the identification of all water-bearing formations can be accomplished up to invasion diameters of 150 inches.

The only problem that may remain unsolved, if an accurate value of R_{xo} is not available, is the accurate determination of R_{xo}/R_t or of R_t when it is not certain that the invasion diameter is within the stated limits. This is where the Proximity Log is of help, as explained in the next section.

INTERPRETATION WITH AN INDUCTION LOG, PROXIMITY LOG, LLs, AND THE SP

When the Proximity Log is available, in addition to an Induction Log and the LLs, it can be used instead of R_{xo} in the chart of Figure 7, in which the abscissae are now entered with the ratio R_{PL}/R_{LLs}.

Making due allowance for the scales of abscissae, which are different in the two cases, it can be observed that Figure 7 is very similar to Figure 6 when the invasion diameter is larger than about 30 inches. This is to be expected since in

[9] A close look at Figure 6 would indicate that the coefficient in relation (3) should be 1.8. The coefficient 2 has been adopted, however, to take into account the probability of a moderate transition zone, as explained later.

[10] As will be discussed later, this condition is particularly easy to detect when the logs are recorded on logarithmic scale, by comparing directly the separation between the resistivity curves and the deflection of the SP.

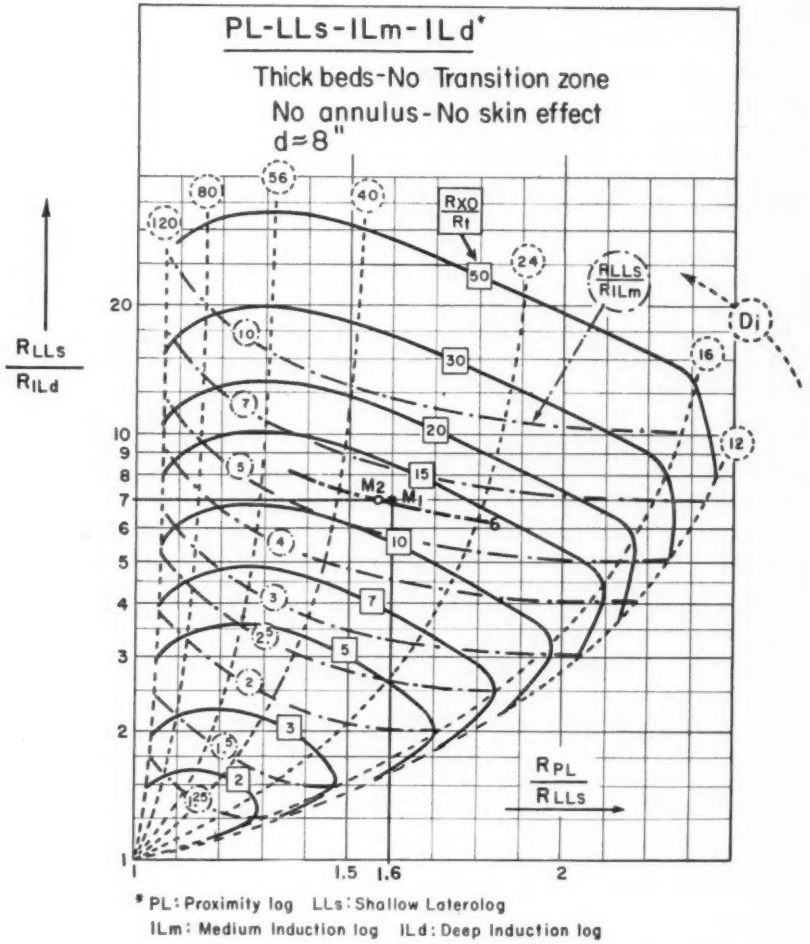


FIG. 7. Interpretation chart, same conditions as Figure 6 except that abscissae are entered with R_{PL}/R_{LLs} instead of R_{xo}/R_{LLs}. Note that the scale of the abscissae is not the same as for Figure 6. Solid point M_1 is plotted by entering with R_{LLs}/R_{ILd} (ordinate) and R_{PL}/R_{LLs} (abscissa). The open point M_2 is plotted from R_{LLs}/R_{ILd} (ordinate) and R_{LLs}/R_{ILm} (dash-dot curves).

that case R_{PL} is practically equal to R_{xo}. For smaller diameters of invasion, the chart is congested because the Proximity Log reading becomes more and more influenced by R_t.

Otherwise there is no difference between the use of Figure 6 with an accurate R_{xo} and the use of Figure 7 with the value of R_{PL}. In either case the chart gives the value of R_{xo}/R_t (interpolated between the solid lines) and the value of D_i

(interpolated between the dashed lines). The important difference is that the value of R_{xo} derived from the Microlog is dependable only when R_{xo}/R_{mc} is smaller than 20, whereas the Proximity Log reading is accurate for the whole range of R_{xo}'s encountered in permeable formations, and for mud cakes up to $\frac{3}{4}$ inch in thickness. This makes the Proximity Log very valuable in consolidated formations.

All the remarks made in the previous section about the direct identification of the water-bearing beds, of course, remain valid, and the chart needs to be used only when the R_{xo}/R_t estimated from 2 $R_{\mathrm{LLs}}/R_{\mathrm{ILd}}$ is definitely smaller than R_{mf}/R_{wa} derived from the SP.

In case of oil saturation, the value of R_{xo}/R_t is smaller than R_{mf}/R_{wa}, even if there is an annulus, and consequently all oil-bearing formations are identified, except, of course, in the unlikely case where the diameter of invasion exceeds the limits of the chart. But if an annulus is present, and if the invasion diameter is fairly large, the value estimated for R_{xo}/R_t from the chart can be somewhat higher than the true value.

Whether or not there is an annulus can be determined, and a better approximation of R_{xo}/R_t obtained, if a second Induction Log is also available, as is discussed in the next section.

For invasions smaller than 40 inches the ILd reads R_t directly, so that R_{xo} can be derived from R_t and R_{xo}/R_t. Conversely R_{xo} is read directly by the Proximity Log when the invasion is larger than 40 inches, so that, in that case, R_t can be derived.

The fact that the value of R_{xo}/R_t is obtained is important for interpretation, particularly in the case of shaly sands.

This section has indicated the possibilities of interpretation with three resistivity curves and the SP, the resistivity devices being the ILd, a short-range radial investigation log (for example the Proximity Log), and the LLs. This combination gives good resolution for D_t, although it might still be improved in the deep invasion region by replacing the LLs with an LLm having a somewhat greater depth of investigation.

Another possible combination of three resistivity curves would be two Induction Logs (ILd and ILm) and the LLs (with no Proximity Log). The ILd-ILm-LLs combination should be excellent for the qualitative detection of oil saturation, but a fourth resistivity curve (e.g., the Proximity Log) would still be needed to detect the annulus, if it exists, and to account for it in determining R_t. With three curves the interpretation would be qualitatively safe but quantitatively uncertain.

INTERPRETATION WITH TWO INDUCTION LOGS, THE LLS, THE PROXIMITY LOG AND THE SP

(1) *Oil-Bearing Formations*

The fact that a bed is oil-bearing is demonstrated by entering Figure 7 with $R_{\mathrm{PL}}/R_{\mathrm{LLs}}$ (in abscissae) and $R_{\mathrm{LLs}}/R_{\mathrm{ILd}}$ (in ordinates), and obtaining a point M_1

corresponding to a value of R_{xo}/R_t, which may or may not be perfectly correct, but in any case is low enough with respect to R_{mf}/R_{wa} from the SP.

If a second Induction Log (ILm) is available, the same Figure 7 can also be entered with R_{LLs}/R_{ILd} (in ordinates) and R_{LLs}/R_{ILm} (by interpolation between the dash-dot lines). This gives a second point M_2, on the chart. If that second point is very close to the first one, there is no appreciable annulus, and the value of R_{xo}/R_t is confirmed. When there is an annulus which appreciably affects the measurements, the second point determined on the chart should be displaced to the right of the first one, and would generally correspond to a higher value of R_{xo}/R_t and to a smaller value of D_i. This should be a positive indication that there is an annulus. If it is desired to get a better evaluation for R_{xo}/R_t in that case, use should be made of charts with annulus (Figure 8). When a good match between the two points can be obtained on one of these charts, that chart will give improved values for R_{xo}/R_t and D_i, and indicate the importance of the annulus.

When the proper chart is found so that M_1 and M_2 coincide, the values found for R_{xo}/R_t and D_i, can, if desired, be used to determine R_t (using $R_{PL}=R_{xo}$ for deep enough invasion or $R_{ILd}=R_t$ for shallow enough invasion). Or the saturation S_w may be determined from

$$S_w = S_{xo}\left(\frac{R_{xo}}{R_t}\,\frac{R_{wa}}{R_{mf}}\right)^{1/2} \tag{4}$$

for clean sands, where R_{wa}/R_{mf} is found from the SP, corrected for ion activity. (Gondouin et al, 1957). S_{xo} must usually be estimated (for example, we may take $S_{xo}\cong 0.8$ or $S_{xo}=\sqrt[5]{S_w}$).

This analysis also gives valuable information on the possible presence of an annulus.

The possible presence of an annular zone of high salinity, between the invaded and non-invaded zones in oil-bearing beds was discovered a few years ago on the basis of laboratory tests. Since then, further laboratory studies and mathematical computations were made[11] to try to define the behavior of the annulus and its effect on Induction Log and other resistivity readings. These have shown that the effect of the annulus on the measurements, for all practical purposes, is equivalent to that of a homogeneous zone of resistivity R_{an} bounded by two coaxial cylinders. The pattern, therefore, includes:

The borehole (negligible effect).

The flushed zone, of resistivity R_{xo} and diameter D_i.

The annulus, of resistivity R_{an}, inside diameter D_i and outside diameter D_j.

The uncontaminated zone, of resistivity R_t.

Computations and experiments have shown that under average conditions the radial thickness of the annulus, $(D_j-D_i)/2$, never exceeds 40 percent of its inside radius, $D_i/2$.

[11] To be published later, when they are complete.

By choosing D_j equal to 1.4 D_i in the construction of the charts, a maximum annulus effect is introduced. The response pattern accordingly involves four parameters: R_{xo}, D_i, R_{an}, and R_t.

In the computation of the corresponding charts, the choice of relevant values for R_{an} is dictated by the fact that R_{xo}/R_{an} is always less than R_{mf}/R_w, since the average residual oil saturation in the flushed zone is necessarily less than in the annulus.

Two specimens of charts computed for R_{xo}/R_{an} equal to 5 and 10 respectively are shown on Figure 8. They are plotted with the same coordinates and the same scales as the chart of Figure 7. The only difference is that the charts of Figure 8 are limited to a maximum value of R_{xo}/R_t equal to 10. There is no point indeed to go further, since for higher values of R_{xo}/R_t the effect of an annulus becomes negligible.

Comparison of Figures 7 and 8 shows that, in case an annulus is present, the plots of R_{LLs}/R_{ILd} vs R_{LLs}/R_{ILm} will then be located to the right of the plots of R_{LLs}/R_{ILd} vs R_{PL}/R_{LLs} on Figure 7 and will even, in many cases, be shifted beyond the right hand limit of the chart.

The annulus problem cannot be properly analyzed unless four well-focused resistivity logs, such as the ones combined here, have been recorded, and oil-bearing formations encountered. To date only a few wells have been logged under these conditions, and there were very few cases of oil-bearing formations. One of them is analyzed in Example No. 2 to be given later.

It is not possible at this time to say how frequently there is an annulus in oil-bearing formations, nor just how much contrast its resistivity shows in practice. There is also some reason to believe that the annulus may fade and even disappear, as a result of diffusion and capillary forces, after a time which may vary, according to the characteristics of the reservoir and of the fluids (permeability, viscosity . . .).

(2) *Water-Bearing Formations*

A complete interpretation in water-bearing formations with all the logs being considered may seem academic and superfluous.

It is important, however, to conduct such a thorough interpretation on a statistical basis, and in various types of formations, for research purposes. In particular, it is important to find out what kind of transition zone may be expected between that part of the invaded zone close to the hole, which has the resistivity R_{xo}, and the uncontaminated zone, which has the resistivity R_t. The presence of a large transition zone could affect the LLs and the Induction Log measurements in opposite directions, with the result that the indications of Figures 6 and 7, which assume no transition zone, would be slightly erroneous. From the results obtained so far, it would seem that this effect is not too large, but if further confirmed by statistics, it might justify the introduction of charts

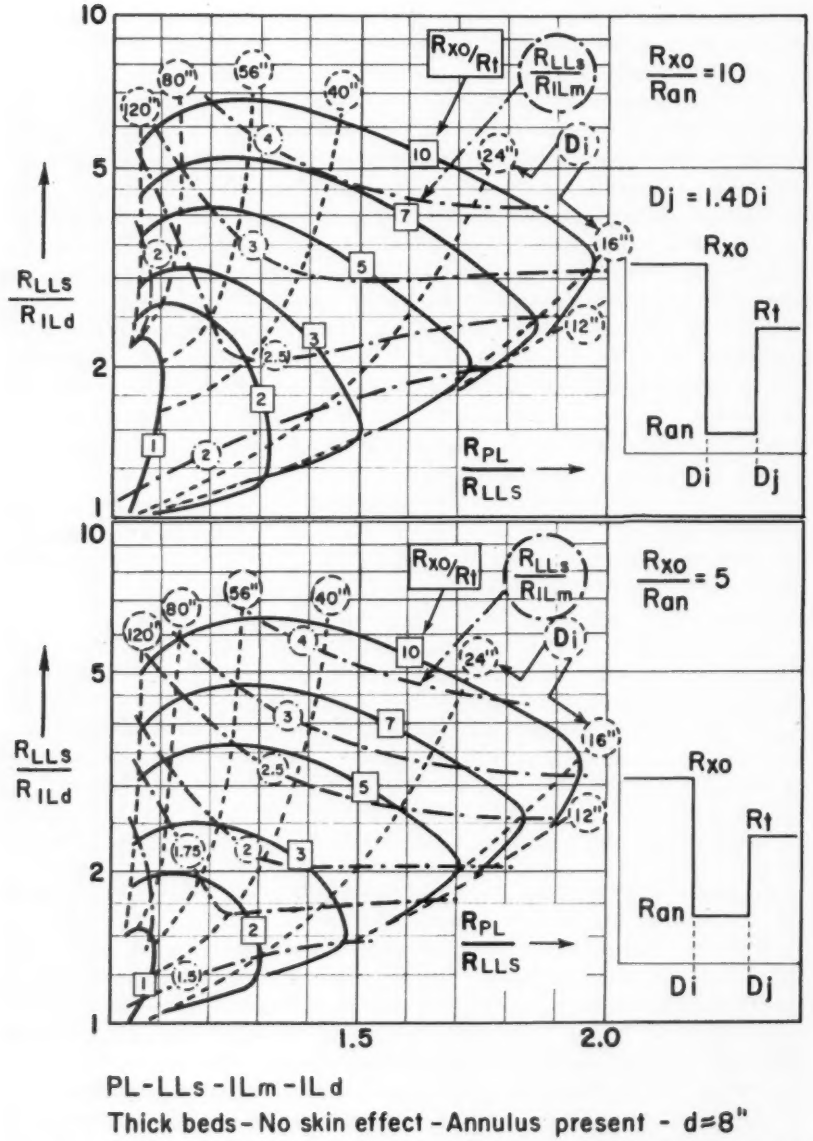


FIG. 8. Interpretation charts using annulus models shown schematically at the right of each chart—thick beds, no skin effect, $d \approx 8$ inches. Upper chart is for $R_{xo} = 10\ R_{an}$, lower chart is for $R_{xo} = 5\ R_{an}$.

similar to those of Figures 6 and 7, in which an average transition zone is taken into account.

It might be interesting to mention here that the effect of a transition zone is in opposite direction to that of an annulus when two points are determined on Figure 7, with R_{PL}/R_{LLs} and R_{LLs}/R_{ILd} for the first point and R_{LLs}/R_{ILd} and R_{LLs}/R_{ILm} for the second. It can be further stated that, in the case of a transition zone, the value obtained for R_{xo}/R_t by Figure 6 or Figure 7 is somewhat too low. This will explain why, in some formations that are obviously water-bearing, the value given by Figure 6 or Figure 7 may be smaller than R_{mf}/R_{wa} by as much as 15 percent, or maybe 20 percent.

Theoretical considerations and laboratory experiments both indicate that a likely explanation for a transition zone is the deeper channeling of the mud filtrate along the more permeable streaks of the formations.

PRACTICAL CONSIDERATIONS

(1) *Use of a Logarithmic Scale*

With the improved resistivity devices described above, the readings are exactly related to each individual bed (provided the bed thicknesses are at least 5 to 6 ft) and are not distorted by the effect of the presence of other media; or if some effect still exists, it can be easily accounted for. Such logs, therefore, are interpreted more easily and accurately than the old ones—with the help of convenient charts, if necessary.

Interpretation can be made still easier if a better presentation (than the present one) is used for the logs. Standard logs are recorded with linear scales. One drawback of this presentation is the need for two, and sometimes three resistivity scales in the same track in regions where the resistivity range is large. When, moreover, the curves for two devices are recorded on the same track, the confusion of curves may become such that the reading of the log is inconvenient, time consuming, and very often erroneous. Another drawback of a linear scale is that the low resistivity portions of the curves are very close to the zero line, and, accordingly, cannot be read accurately. Improved presentations of the logs have, therefore, been sought.

To date, it seems that an improved presentation is obtained by the use of a logarithmic scale for the resistivity curves. The advantage of this scale for the clarity of the readings, is illustrated in Figure 9, where two portions of a log, recorded in the Mid-Continent, with the LLs and 6FF40, are shown. The linear and logarithmic scales, are reproduced for comparison. The gray stripes across the log denote the impervious sections, as determined from the Microlog and Microcaliper log (not shown on the figure).

Another feature of interest in the use of the logarithmic scale is that the ***ratio*** between the readings of two resistivity devices at the same level is given directly by the separation between the two curves. This point may be of assistance in the qualitative interpretation, as will be explained in the next subsection.

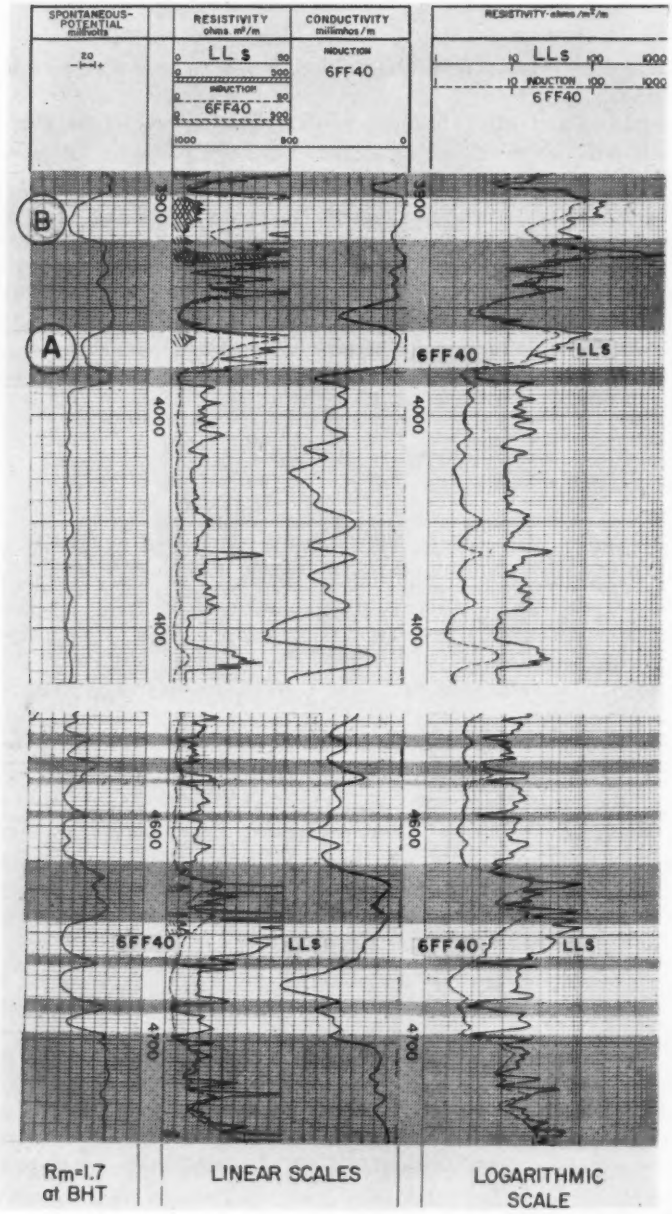


FIG. 9. Comparison of linear-scale (center track) and logarithmic-scale (right-hand track) recordings of LLs and 6FF40. The gray stripes on the log denote intervals indicated to be impervious by Microlog and Microcaliper log (not shown).

(2) *Simplified Estimation of* R_{xo}/R_t.

Some water-bearing beds can be discarded, using the combination LLs, ILd, and SP.

One way to locate the water-bearing formations is to compare the value of R_{xo}/R_t with that of R_{mf}/R_w in clean sands (derived from the SP curve or from statistics), or with that of R_{mf}/R_{wa} in shaly sands (derived from the SP curve). If these two ratios are about equal, it can be safely concluded that the formation is water-bearing. If R_{xo}/R_t is definitely smaller than R_{mf}/R_w, the formation is likely to contain hydrocarbons.

Furthermore, a simple, though approximate, relationship between a given value of R_{xo}/R_t and the corresponding value of $R_{\mathrm{LLs}}/R_{\mathrm{ILd}}$ can be determined.

It is easily verified on the chart of Figure 7 that, when D_i remains between the limits 24 inches and 150 inches, the ratios R_{xo}/R_t and $R_{\mathrm{LLs}}/R_{\mathrm{ILd}}$ satisfy the following relationship provided $R_{xo}/R_t > 5$.

$$\frac{R_{xo}}{R_t} = 1.8\,\frac{R_{\mathrm{LLs}}}{R_{\mathrm{ILd}}} \qquad \text{within } \pm 20 \text{ percent.} \tag{5}$$

On a chart for the case of a transition zone, the above relationship might become:

$$\frac{R_{xo}}{R_t} \approx 2.5\,\frac{R_{\mathrm{LLs}}}{R_{\mathrm{ILd}}}$$

with somewhat wider limits for D_i.

In general, therefore, and for all practical purposes, R_{xo}/R_t can be taken equal to 2 $R_{\mathrm{LLs}}/R_{\mathrm{ILd}}$, even though the invasion diameter varies between rather broad limits.[12]

The detection of the water-bearing beds is accomplished by comparing the values of 2 $R_{\mathrm{LLs}}/R_{\mathrm{ILd}}$ with R_{mf}/R_w. Wherever the resistivity ratio of mud filtrate and formation water can be taken as being approximately equal to the activity ratio, the procedure is equivalent to comparing K log (2 $R_{\mathrm{LLs}}/R_{\mathrm{ILd}}$) with the SP deflection.

On a logarithmic scale recording, the value of $R_{\mathrm{LLs}}/R_{\mathrm{ILd}}$ is measured by the separation between the LLs and the ILd curves. This should make possible a quick and easy detection of the water-bearing beds under favorable conditions as for example, when the SP is uniform over thick permeable sections. Moreover, in such a favorable case, the two resistivity curves should be sensibly parallel to each other, over all water-bearing beds.

[12] The equivalent relation for the 5FF40 would be

$$\frac{R_{xo}}{R_t} = 2.75\,\frac{R_{\mathrm{LLs}}}{R_{\mathrm{ILm}}} \pm 30 \text{ percent}$$

with 20 inches $< D_i <$ 80 inches.

The logs traced in Figure 9 give an example in which visual interpretation is straightforward: The SP deflection is very uniform, and on the logarithmic scale the separation between the two resistivity curves is practically constant through the two intervals shown, except at the levels of beds A and B (which are known to contain hydrocarbons).

Visual interpretation is not always so easy. The permeable beds may be comparatively thin, and separated by thick shales; the lithology and, hence the formation factor may vary rapidly within the beds; and the SP deflection may be diversely affected by variable shaliness and bed thickness effects. Further experiments will be necessary to assess the reliability of this approach.

FIELD EXAMPLES

Example No. 1

The example of Figure 9 shows the use of the logarithmic scale for the Induction Log (ILd) and the shallow investigation Laterolog (LLs) on the right track, with the same logs recorded on the usual linear scale, for comparison, in the center track.

The advantage of the logarithmic scale for the clarity of the log is illustrated to some extent by the section below 3,900 where, on the linear log, the second scale curve (0–500 ohm-m) comes into the picture, and makes the logs difficult to read. For larger ranges of resistivities, as are frequently encountered, the appearance of the linear log would be even more complicated.

On the linear presentation, and in the thick permeable bed between 4,000 and 4,100 ft, the Induction Log readings must be taken from the conductivity scale, because on the resistivity scale the curve is too close to the zero line. It makes the comparison with the LLs, and the determination of R_{LLs}/R_{ILd} at various levels, rather difficult. On the contrary, the two curves on the logarithmic scale remain almost perfectly parallel (i.e., they have constant separation) over the whole interval, and it is very easy to see, from the logarithmic scale recording, that the ratio R_{LLs}/R_{ILd} remains close to 5. Assuming that the invasion diameter is between the proper limits, and using relation (3):

$$\frac{R_{xo}}{R_t} \approx 2\,\frac{R_{LLs}}{R_{ILd}} = 10.$$

This checks with the SP, from which, after correction for ion activities, the value of $R_{mf}/R_{wa} = 11$ is derived. Therefore the conclusion is that the whole section is unquestionably water-bearing.

It can be noticed on the log that, for beds A and B, the separation between the resistivity curves is much less; no plateau is observed which would make the interpretation easier, but the curves are parallel, and the constant separation within each permeable bed corresponds to a ratio R_{LLs}/R_{ILd} of 2.

If the invasion is within the proper limits for these two beds, this means a

ratio R_{xo}/R_t of 4. This is much too low to match R_{mf}/R_{wa} from the SP, and, consequently, strongly suggests oil saturation. To be completely on the safe side, this conclusion should, however, simply be considered as a probability, justifying a final check with the help of R_{xo} (from the Microlog) or R_{PL}, by use of the proper chart (Figure 6 or Figure 7). In this particular case, the tentative conclusion was confirmed by use of R_{PL} and the chart of Figure 7.

Example No. 2

In Figure 10, the center section of the sand bed, between 8,120 ft and 8,129 ft, has been the subject of a complete interpretation by means of all the electrical logs available (ILd, ILm, LLs, PL, and SP).

The resistivity readings are:

$$R_{PL} = 65 \qquad R_{ILm} = 25$$

$$R_{LLs} = 59 \qquad R_{ILd} = 25.$$

Hence:

$$R_{PL}/R_{LLs} = 1.1$$

$$R_{LLs}/R_{ILd} = 2.36$$

$$R_{LLs}/R_{ILm} = 2.36.$$

In a first interpretation by means of Figure 11 (chart for no transition zone and no annulus, basically the same chart as Figure 7), a point M_1 is plotted by entering with R_{PL}/R_{LLs} (in abscissae) and R_{LLs}/R_{ILd} (in ordinates). To indicate a possible uncertainty of ± 5 percent in the ratios of the log readings, the points have been surrounded by a cross-hatched rectangle ($2.48 > R_{LLs}/R_{ILd} > 2.24$ and $1.15 > R_{PL}/R_{LLs} > 1.05$).

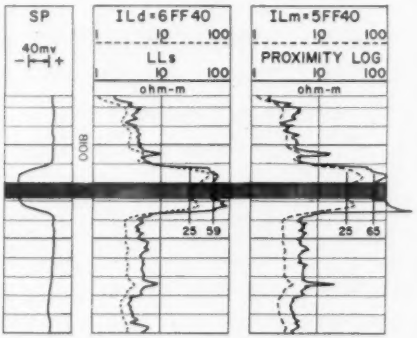


FIG. 10. Logs used in Example no. 2, interpreted to be a case of annulus. For convenience, the ILm and PL, although recorded on separate runs, have been traced together in the right-hand track.

As seen in the plot of Figure 11, M_1 indicates a value of R_{xo}/R_t of about 3.4, with the uncertainty indicated by the cross-hatched rectangle.

Since the indicated invasion is deep (between about 70 inches and 110 inches) R_{PL} would read R_{xo} and we find $R_t = R_{xo}/(R_{xo}/R_t) \approx 65/3.4 = 19$; that is, $R_t \approx 0.76 R_{ILd}$.

In a check on the same chart, entering with R_{LLs}/R_{ILd} (ordinate) and R_{LLs}/R_{ILm} (dash-dot curves), the point, M_2, plots well to the right of M_1, in fact beyond the limits of the chart. (Again a ± 5 percent uncertainty in the ratios is indicated by the cross-hatched area.)

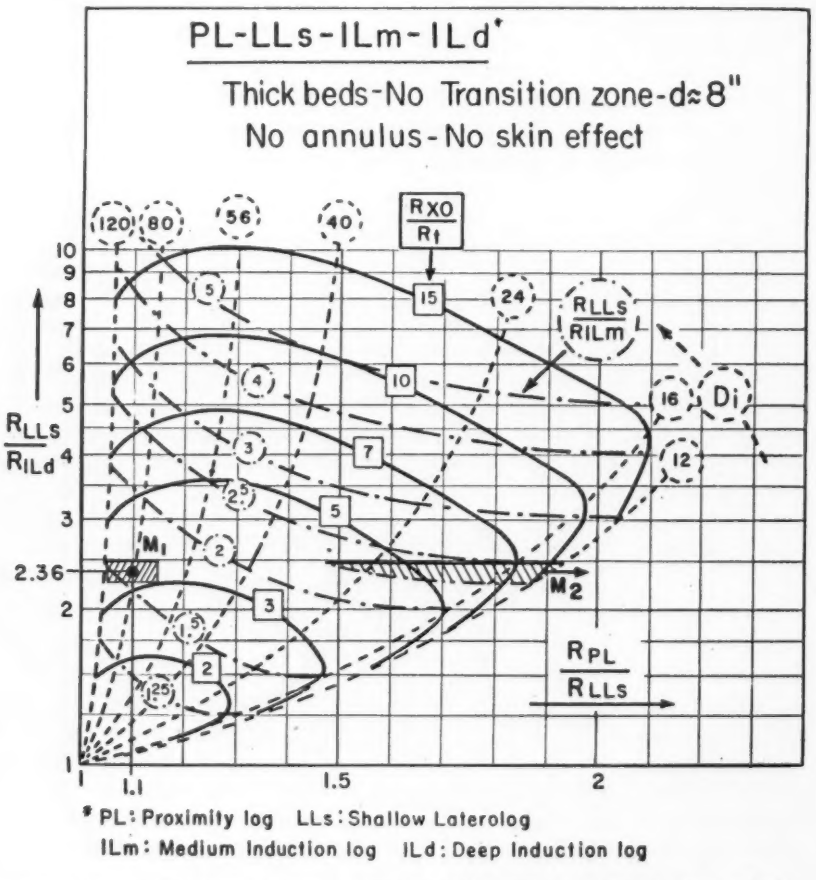


FIG. 11. Plot on basic chart of Figure 7 of data from field example of Figure 10. Cross-hatched areas show effect of ± 5 percent uncertainty in plotted values.

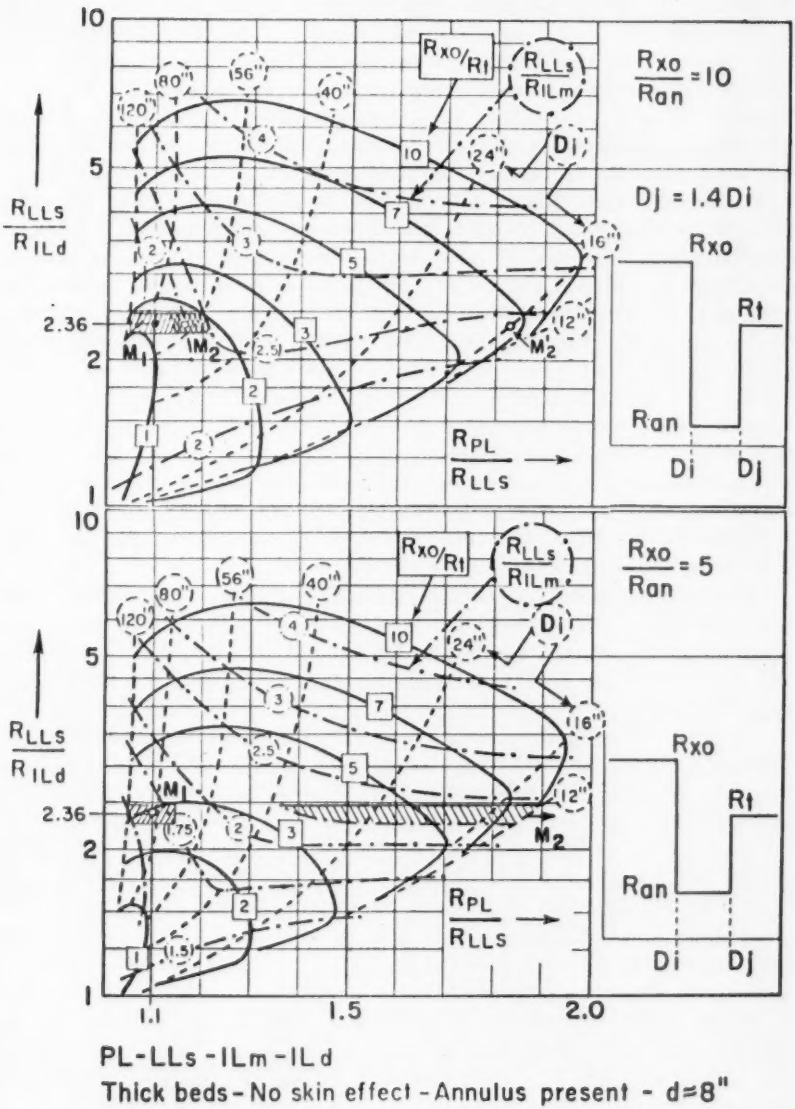


FIG. 12. Plots on annulus charts of data from field example of Figure 10. Cross-hatched areas show effect of ±5 percent uncertainty in plotted values.

The fact that M_2 and M_1 are widely separated indicates that the readings of the four resistivity devices are not mutually consistent for the conditions of this chart (i.e., no transition zone and no annulus). The fact that M_2 plots well *to the right* of M_1 on this chart is indicative of the presence of an annulus.[13]

Next, the data are plotted on the annulus chart for $R_{xo}/R_{an}=5$ (lower chart of Figure 12). Again M_2 plots well to the right of M_1, indicating that this chart does not have sufficient annulus effect to fit the data.

When the data are plotted on the upper chart of Figure 12 (for $R_{xo}/R_{an}=10$) there are two possible M_2 points. The one corresponding to shallow invasion, designated as M_2', is ruled out as inconsistent with the M_1 point. The M_2 point corresponding to deep invasion is, however, rather close to M_1, and, in fact, their areas of uncertainty overlap slightly. However, the point M_2 still plots slightly to the right of M_1. Most probably there is in this example an annulus slightly more important than the one assumed in the upper chart of Figure 12 ($R_{xo}/R_{an}=10$).

If the points M_1 and M_2 were plotted on a chart for R_{xo}/R_{an} somewhat larger than 10, the coincidence of M_1 and M_2 would be further improved. Also, on such a chart, the R_{xo}/R_t lines would be shifted further. As a result, the final value of R_{xo}/R_t would be close to, but probably less than, 1.3, the value indicated by M_1 in the upper chart of Figure 12. (Compare this value, 1.3, with the 3.4 indicated by point M_1 on Figure 11.)

Since invasion is deep we can take $R_{xo}=R_{PL}$. Thus we find $R_t=65/1.3=50$. Note that R_t is actually larger than R_{ILd} (equal to 2 R_{ILd}) in this annulus case. Compare this result with the conclusion that $R_t\approx 0.76\ R_{ILd}$ from point M_1 of Figure 11, which was based on a knowledge of only R_{ILd}, R_{LLs}, and R_{PL} (and no knowledge of R_{ILm}).

From the SP we find $R_{wa}=0.14$ and $R_{mf}/R_{wa}=7.15$. By comparing this value with the final value of R_{xo}/R_t found above, the presence of hydrocarbons is safely predicted. Using the R_{xo}/R_t method[14] we find $S_w=34$ percent if the sand is clean and $S_w<34$ if the sand is shaly (i.e., if R_w is actually less than 0.14).

It is further interesting to note in this example that entering the chart of Figure 11 with only a knowledge of ILd, ILm, and LLs (and no knowledge of R_{PL} or R_{xo}) would have led to the interpretation indicated by point M_2 (i.e., shallow invasion and some uncertainty in the value of R_{xo}/R_t). One would conclude that the Induction Logs are reading R_t directly (i.e., $R_t=25$). However, if one can introduce the additional information, derived from the Sonic Log on the well, that $F=27$, it is possible to estimate $R_o=FR_{wa}=27\times 0.14=3.8$. The fact that R_t is apparently about $6\frac{1}{2}$ times as great as R_o is a clear indication of saturation. Thus, although this interpretation is not quantitatively as exact, the oil sand would not have been missed.

[13] If M_2 had plotted to the left of M_1 on this chart a transition zone would have been indicated.

[14] Chart D-4 of Schlumberger Log Interpretation Charts.

CONCLUSION

The great majority of the water-bearing formations can be identified as such with only one or preferably two resistivity logs, namely:

(a). The deep Induction Log, if the resistivity reading R_{ILd} *is not appreciably larger than* R_o as determined from the SP and a porosity determination. However, this criterion applies only when the formations are known to be reasonably clean.

(b). The deep Induction Log and a short Laterolog, if *the ratio of their readings shows that* R_{xo}/R_t *is not much smaller than* R_{mf}/R_{wa} as determined from the SP. This method is greatly facilitated by the use of a logarithmic scale for both resistivity logs.

When either of the conditions italicized in (a) or (b) is satisfied, the identification of the formation as water-bearing is not ambiguous, and there is no need to check on the depth of invasion.

Because most permeable formations are water-bearing and most of them can be identified as just explained, there is a temptation to jump to the conclusion that only two resistivity logs are needed in all cases, especially when the porosity is determined, in addition, for example by a Sonic Log.

It turns out, however, that when neither condition (a) nor condition (b) above is satisfied there is generally no safe way to make the interpretation. In such a case, the formation can be oil-bearing, but it can be water-bearing and deeply invaded, and there is generally no safe way to differentiate between these two quite different interpretations, unless a third resistivity log is available.

With three resistivity logs the qualitative interpretation, i.e., the distinction between water-bearing and oil-bearing formations, is safe in all cases, but the quantitative determination of R_t and consequently that of S_w can be erroneous if there is an annulus and deep invasion.

To find out whether there is an annulus, and to obtain as accurate a value of R_t as possible, a fourth resistivity curve is necessary; it is not as accurate to replace that fourth resistivity curve by a value of R_{xo} computed from the porosity and R_{mf}.

The recording of four properly selected resistivity curves, as described in this paper, is therefore highly desirable. With the addition of the SP and a porosity log—for example the Sonic—all the information for good quantitative interpretation would thus be available, and the interpretation would not only be safer but, in fact, simpler.

These conclusions show that the means for recording, preferably in not more than two runs, four resistivity curves, with the SP, a porosity log, a Microcaliper, and also, if possible, a Microlog, would constitute a considerable progress in logging technique.

ACKNOWLEDGMENTS

The authors acknowledge the valuable contributions of M. Gondouin, who designed the laboratory setup for the study of invasion, conducted the experi-

ments and derived the conclusions. They wish to express their appreciation to J. Kellough and his co-workers of the field testing section who recorded the experimental logs, and to the personnel of the field locations who cooperated in performing the measurements. They are indebted to R. Sauvage for his thorough and detailed analysis of the logs and to F. Segesman and J. Lebel for their help in the computation of the charts. Acknowledgments are due also to S. L. Showah, who carried out the measurements on the resistor network analog, and to W. Hamer, who performed the tests with the electrolytic tank. The valuable assistance of F. Segesman and M. C. Watson in the preparation of the paper is appreciated.

The authors wish to thank the various oil companies who kindly made possible the performance of field tests.

REFERENCES

Campbell, W. M., and Martin, J. L., 1955, Displacement logging—a new exploratory tool: Trans. AIME, v. 204, p. 233–239.

Dumanoir, J. L., Tixier, M. P., and Martin, M., 1957, Interpretation of the induction-electrical log in fresh mud: Trans. AIME, v. 210, p. 202–217.

Gondouin, M., Tixier, M. P., and Simard, G. L., 1957, An experimental study on the influence of the chemical composition of electrolytes on the SP curve: Trans. AIME, v. 210, p. 58–72.

Tixier, M. P., Alger, R. P., and Tanguy, D. R., 1960, New developments in induction and sonic logging: Journal of Petroleum Technology, v. 12, n. 5, p. 79–87.

GEOPHYSICS, VOL. XXV, NO. 4 (AUGUST, 1960), PP. 883–890

RADIOACTIVITY LOGGING AND ITS FUTURE POTENTIAL*

EDWIN S. MARDOCK†

ABSTRACT

The quantitative application of radioactivity logs for the estimation of formation petrophysical properties is dependent on certain fundamental factors which are discussed. It is difficult to avoid "hybrid" combinations of processes; for example neutron-neutron and neutron-gamma effects together, however, it is believed that the future of quantitative application of neutron logs depends to a large extent on the development of single component logging processes. Positive location of the sonde within the borehole for all types of logs needs further development. These improvements plus future developments in gamma-ray spectral logs, neutron-gamma spectral logs, neutron activation logs, and neutron inelastic scattering logs promise a bright future for radioactivity logging.

INTRODUCTION

Two decades have passed since radioactivity well logging was first introduced commercially. The use of radioactivity logs has increased steadily; however, the relative use of radioactivity logs compared with other types still remains small and there is no question that a degree of technical inferiority in its capabilities for quantitative work has been responsible.

From the time of their introduction, the chief value of the logs has rested on their capability of delineating lithology in a satisfactory manner in the open hole and through casing. Because of this, they became widely used in a number of applications such as: stratigraphic correlation work, measurement checks on the location of casing shoes and collars and the location of potential pay through casing in order to guide the gun perforating operation.

Today, however, a log must be capable of quantitative interpretation with respect to some fundamental property of the formation or the fluids contained therein or it faces eventual replacement by a log which can be quantitatively interpreted. There is a growing impression that radioactivity logs are undependable as sources of quantitative information while other types of new logs are capable of supplying quantitative information. The impression regarding the relative merits of radioactivity logs compared to the new types of logs is believed to be in error insofar as the potential of radioactivity logs is concerned, although there is justification for it in the log qualities sometimes observed.

QUANTITATIVE RADIOACTIVITY LOGGING

Progress in the development of quantitative radioactivity logs has been slow for two principal reasons. First, there has been a lack of information with respect to some of the basic physical processes involved in radioactivity well logging, and second, there has been a lack of understanding of the environmental factors which control and limit the application of the logs.

* Manuscript received by the Editor April 29, 1960.
†Consultant, Tulsa, Oklahoma.

The main physical processes involved with respect to the effect of formation properties on radioactivity logging include: the scattering and absorption of gamma-ray photons, the elastic and inelastic scattering of neutrons and neutron capture. The gamma-ray processes which include the natural gamma-ray log and the induced gamma-ray or gamma-gamma log used for density logging are influenced mainly by the density of the formation, while the neutron processes are influenced primarily by its chemical composition and to a much lesser degree by its density. The neutron-gamma process (bombarding the formation with neutrons and recording the resulting gamma rays) is influenced to a somewhat greater extent by the density although this difference is of about the same order of magnitude as the differences observed in the response to chemical composition by the various neutron-neutron processes.

Radioactivity logs are inherently more highly influenced by the environment closest to the sonde; hence, have shallow depths of investigation and are sensitive to borehole influence such as diameter, mud weight, casing and cement thickness and the position of the logging tool in the borehole.

Because of the substantial effect on the log of the position of the logging tool within the borehole, it is important that the position of the tool be fixed insofar as it is possible by means of centralizing or decentralizing springs or arms. In addition, its actual distance from the well face should be determined by means of a stand-off indicator to indicate mud cake thickness for the decentralized position or a caliper for use with the centralized position. Experience will eventually determine which procedure is best for a specific tool and log.

Generally speaking, the gamma-ray log is the least affected by such factors as borehole diameter, mud properties, casing and cement thickness, while the neutron logs including both the so-called neutron-gamma logs and neutron-neutron logs are most seriously affected by these and other factors.

"HYBRID" OR MULTICOMPONENT LOGS

Because fast neutrons, slow (thermal) neutrons and gamma rays all react differently to both borehole and formation conditions, the response of the log will depend on the types of radiation detected and the relative abundance of each type.

Due to the lack of information concerning these physical processes and because it is technically difficult to avoid making measurements which combine several physical processes, many of the logging instruments run commercially have produced "hybrid" combinations of the neutron-neutron and neutron-gamma processes as well as combinations of the gamma-gamma and the neutron-gamma processes. These combinations give results which cannot always be applied quantitatively. The reduction of such effects is a primary step in the improvement of radioactivity logs.

It is an inescapable conclusion that pure or single component neutron logs will lead to more quantitative measurements. Usually the term "single-com-

ponent" means the use of a detector which is responsive to only one kind of radiation or to radiation of a definite energy range. For example, a neutron-gamma log should be made by a detector which "sees" only the gamma radiation produced by neutron bombardment and does not "see" either the scattered gamma radiation originating in the gamma rays emitted by the source, or neutrons returning to the logging sonde.

FACTORS AFFECTING THE QUANTITATIVE INTERPRETATION OF RADIOACTIVITY LOGS

Many factors associated with borehole conditions, the formations, and instrument performance, affect the quantitative application of radioactivity logs. Those are as follows:

I. For the Gamma-Ray Log:

1. Density of the well fluid.
2. Borehole diameter.
3. Thickness of the casing and cement.
4. Position of the detector in the borehole.
5. Gamma-ray spectrum of the source.
6. Density of the formation.
7. Radioactivity of the borehole fluid.
8. Radioactivity of the formation material.
9. Logging speed, time constant and sampling length.
10. Bed thickness.

It is presumed that the detector response characteristics are already known. It is obvious that the effects of the nine other factors must be known or controlled in order to determine the radioactivity of the formation.

II. For Gamma-gamma Logs:

In general, the same factors apply to gamma-gamma logging as to gamma-ray logging with a few exceptions. The radioactivity of the borehole fluid and the formation are seldom high enough to produce any effect on the measurements and a capsule source of known gamma-ray energy spectrum is substituted for formation as the source of gamma rays. The effect of borehole diameter is greater and two new factors have been added, e.g., the source-detector spacing and the necessity of controlling the position of both the detector and the source within the borehole. This has been done in the commercial instruments by means of a decentralizing spring.

Gamma-gamma logs calibrated in terms of density have given perhaps the most consistent and the most accurate results of all radioactivity logging. This is due to the fact that the gamma-gamma log is a single process log and because it is carefully positioned in the borehole. The greatest accuracy is obtained when the borehole is smooth and free from mudcake. The addition of an indicator to

show the standoff distance of the instrument from the well face should improve the use of the log *when* a mud cake is present or *when* the borehole is rough.

III. For Neutron Logs:

1. The composition of the rock.
   a. With respect to the hydrogen content.
   b. With respect to thermal neutron capture or scattering or capture cross sections.
   c. With respect to fast neutron scattering cross sections.
   d. With respect to the neutron-gamma response.
2. The density of the rock.
3. The density of the borehole fluid.
4. The composition of the borehole fluid.
5. The borehole diameter.
6. Casing and cement thickness.
7. The position of the source and the detector in the borehole.
8. The source-detector spacing.
9. The source strength and neutron spectrum.
10. Gamma-gamma effects (these interfere with neutron-gamma logs only).
11. Time constant, logging speed, and sampling length.
12. Bed thickness.

A consideration of the above list leads to certain definite conclusions respecting the quantitative uses of neutron logs. To determine porosity, for example, the neutron log chosen should respond as exclusively as possible to epithermal neutrons; otherwise it will be unnecessarily sensitive to undesirable parameters. Items 2, 3, 4, 5, 6, 7, 8, and 9 must be known or held constant. The gamma-gamma response, 10, is never desirable in a neutron log run for quantitative purposes. It is both misleading as to its real influence and deleterious in its effects on the response of the log to porosity.

To determine chlorine as for example in the problem of identifying water and oil zones behind casing it is fairly obvious that more than one log will be required because it is necessary to determine the fractional void space containing the fluid as well as the amount of chlorine contained therein. This can be done by any of the following comparisons:

(1) The thermal neutron-neutron log vs the neutron-gamma log.
(2) The thermal neutron-neutron log vs the epithermal neutron-neutron log.
(3) The neutron-gamma log vs the epithermal neutron-neutron log.

The first comparison will normally give the greatest effect due to chlorine although when other elements exhibiting neutron-gamma effects are present the effectiveness is reduced.

The second combination is the least sensitive of the three to the presence of chlorine but offers the advantage that it is affected the least by the presence of other elements because there are only a limited number of elements found in reservoir rocks which exhibit thermal neutron capture cross sections.

The third combination offers the advantages of including the best porosity log in the epithermal neutron-neutron log and the deeper penetration of the neutron-gamma log. However, the latter is also influenced by the neutron-gamma reactions to other elements within the rock.

Possibly the ideal arrangement to detect chlorine under all circumstances is to run all three logs simultaneously.

NEUTRON LOG STANDARDIZATION

Attempts are now being made by the industry to standardize the performance of the various types of commercial neutron logs with respect to their responses to porosity. This is, of course, a very worthy objective and it is to be hoped that progress in this direction will result from the effort. However, the majority of the tools now being used to obtain commercial logs are sensitive to many parameters other than porosity and the procedures proposed to date do not make provision for calibrating the tool response to all major factors.

It is evident that it will only be possible to standardize a neutron logging tool if its response to all factors is known. This will certainly be impossible for any logs but those presenting the least complicated behavior, namely, the single component thermal neutron-neutron log, the single component epithermal neutron-neutron log, or the single component neutron-gamma log. In addition, its position in the hole must be known both at the time of standardization and at the time logs are run in order for the standardization data to be meaningful.

PRESENT STATUS OF RADIOACTIVITY LOGGING

The present status of radioactivity well logging might be summarized in the light of the preceding discussions as follows:

(1) The radioactivity well logging equipment now in use is very much superior to that available a decade ago with respect to reliability, ruggedness, temperature stability and statistical performance. The original applications for gamma-ray and neutron logs requiring only qualitative interpretation have been extended through the introduction of small diameter logging tools for through-tubing use.

(2) The quantitative applications of radioactivity logs have been extended mainly through the utilization of the gamma-gamma log calibrated in terms of density. In some instances it has been used quite successfully to estimate porosity. A fair degree of success has been attained in the identification of cased off water or oil producing zones by the comparison of two neutron logs of different characteristics. The estimation of porosity is still successful only in those areas where empirical calibration techniques are feasible and where reliable zones for reference occur in the well and are located relatively close to the zone of interest.

Generally speaking, the status of quantitative interpretation of neutron logs has not advanced in recent years. A suggestion to improve this situation appears to be to develop single component logs; to incorporate devices to both fix the position of the logging tool in the borehole and determine its position with respect

to the well face; and to include the other factors controlling the application of the logging process within the interpretation procedure for the logs.

FUTURE DEVELOPMENTS

New radioactivity logging developments which may be introduced in the near future are: neutron activation logs neutron-gamma-ray spectral logs and natural gamma-ray spectral logs. In addition, the advent of the accelerator neutron source now undergoing development in several laboratories, will undoubtedly introduce a number of new logging methods which are made possible by the 14 Mev neutrons produced by this source. These may include the same kinds of single process neutron logs previously discussed but capable of deeper investigation due to the greater penetration obtainable with the more energetic neutrons.

New logs which may find an important place in the identification of oil bearing strata are dependent on the activation of oxygen due to the n,p reaction of 14 Mev neutrons with oxygen,

$$O^{16}(n, p)N^{16} \Big| \xrightarrow[7.3s]{\beta, \gamma} O^{16},$$

and the inelastic scattering of neutrons by carbon,

$$C^{12}(n, n, \gamma)C^{12}.$$

The oxygen log is made by observing gamma rays (6.3 Mev) produced by the decay of the N^{16} produced in that reaction.

The carbon log is made by selectively detecting the characteristic gamma rays produced instantaneously by carbon when bombarded by fast neutrons. A particularly advantageous way to accomplish this is to pulse the output of the accelerator source and observe the 4.4 Mev gamma rays from carbon at the beginning of each pulse of neutrons.

Tittmann and Nellgan have pointed out the possibility and the advantages of using a pulsed accelerator source to measure both the inelastic scattering radiation and that due to neutron capture for the detection of many elements by source pulsing techniques.

The accelerator source neutrons are capable of activating elements in the formation or in the brine by other n,p reactions. For example, a silicon measurement is readily possible based on the following n,p reaction:

$$Si^{28}(n, p)Al^{28} \Big| \xrightarrow[2.3\ \text{min}]{\beta, \gamma} Al^{27}.$$

It is interesting that thermal neutrons react with aluminum to produce the same isotope:

$$Al^{27}(n, \gamma)Al^{28}$$
$$\xrightarrow[2.3\ \text{min}]{\beta, \gamma} Al^{27}.$$

The 14 Mev accelerator-produced neutrons also react with aluminum by an n,p reaction to produce a different isotope:

$$Al^{27}(n, p)Mg^{27}$$
$$\xrightarrow[9.6\ \text{min}]{\beta, \gamma} Mg^{26}.$$

These activation reactions of aluminum and silicon may well serve as the basis for the development of a clay log which should prove to be extremely useful as an interpretative aid to electric logging as well as neutron porosity logs made in shaly sands or silty limestones.

An n,p reaction with chlorine may offer possibilities for another approach to the problem of identifying cased-off brine or oil bearing formations:

$$Cl^{37}(n, p)S^{37}$$
$$\xrightarrow[5.4\ \text{min}]{\beta, \gamma} S^{36}.$$

It should again be emphasized in connection with these prospective developments that their true value may not be realized unless the factors now affecting the application of standard gamma-ray and neutron logs also are considered.

CONCLUSIONS

The full potential value of radioactivity logging has not been realized in part due to the fact that some of the important factors have not yet been fully considered with respect to either the design of the equipment or the interpretation of the logs.

The future quantitative application of radioactivity logs will depend on the success of developing single-component logging processes.

New developments in the future may provide neutron activation and inelastic scattering logs which will be useful in identifying some elements and thus predict lithology and in locating oil-bearing zones; gamma-ray spectral logs to estimate Uranium, Thorium, Potassium ratios; useful for identifying formations; neutron-gamma-ray spectral logs for the identification of chlorine and other elements exhibiting neutron-gamma effects.

ACKNOWLEDGMENT

The author gratefully acknowledges the constructive discussions of the material of this paper with J. J. Pickell of Shell Development Company (Division of Exploration and Production Research), Houston, Texas, and Mr. Arthur H. Youmans of Well Surveys, Inc., Tulsa, Oklahoma.

REFERENCES

Baker, P. E., 1957, Density logging with gamma rays: J. Pet. Tech., v. 9, n. 10, 289.

——— 1957, Neutron capture gamma-ray spectra of earth formations: J. Pet. Tech. v. 9, n. 3, 97.

Belknap, W. B., 1959, Standardization and calibration of nuclear logs: Petroleum Engineer B-24.

Brannon, H. R., 1956, Osoba, J. S., Spectral gamma-ray logging: J. Pet. Tech., v. 8, n. 2, 30.

Bush, R. E., and Mardock, E. S., 1950, Some preliminary investigations of quantitative interpretation of radioactivity logs: J. Pet. Tech., v. 2, n. 1, 19.

——— and Mardock, E. S., 1951, The quantitative application of radioactivity logs: J. Pet. Tech., v. 3, n. 7, 191.

Caldwell, R. S., and Sippel, R. F., 1959, New developments in radioactive well logging research: Bull. A.A.P.G. 42, n. 1.

——— 1958, Using nuclear methods in oil well logging: Nucleonics.

Dewan, J. T., and Allaud, L. A., 1953, Experimental basis for neutron log interpretation: Petroleum Engineer 25, no. 9, B-49.

——— 1956, Neutron log correction charts for borehole conditions and thickness: J. Pet. Tech., v. 8, n. 2, 50.

Flerov, G. N., Alexeyev, F. A., Dakhnov, V. N., Gulin, Yu. A., and Shimelevitch, Y. S., Use of methods of atomic physics in oil and gas prospecting and production: paper presented at 5th World Petroleum Congress, 1959.

Green, W. G., and Fearon, R. E., 1940, Well logging by radioactivity: Geophysics, v. 5, p. 272.

Martin, R. I., 1955, Logging with gamma-ray and neutron techniques: Oil and Gas Journal, v. 53, n. 40, 121.

Mott, William E., and Ediger, Nicholas M., Nuclear well logging in petroleum exploration and production: paper presented at 5th World Petroleum Congress, 1959, Section X, paper No. 16.

Newton, G. R., Skinner, J. E., and Silverman, D., 1954, Subsurface formation density logging: Geophysics, v. 19, p. 636.

Rabson, W. R., 1959, Chlorine detection by the spectral log: Petroleum Engineer, n. 5, 193.

——— P.G.A.C. nuclear well logging porosity evaluation charts for the PH-125 neutron-neutron log: Bulletin of the Pan Geo Atlas Corporation.

Russell, J. H., and Bishop, B. O., 1954, Quantitative evaluation of rock porosities by neutron-neutron method: Petroleum Engineer, v. 26, n. 4, B-76.

Russell, W. L., 1952, Interpretation of neutron well logs: Bull, A.A.P.G., v. 36, p. 312.

——— 1941, Well logging by radioactivity: Bull. A.A.P.G., v. 25, p. 1768.

Scotty, C. B., and Egan, E. F., 1952, Neutron derived porosity-influence of borehole diameter: J. Pet. Tech., v. 4, n. 8, p. 203.

Stroud, Stanley G., and Schaller, Herman C., 1960, A new nuclear log for the determination of reservoir salinity: J. Pet. Tech. p. 37.

Tittmann, J., and Nellgon, W. B., 1959, Laboratory studies of a pulsed neutron source technique in well logging: A.I.M.E. paper n. 1227-G, presented at Casper, Wyoming meeting.

Toelke, L. W., 1955, Scintillation spectrometer well logging: A.I.M.E. paper 495-G presented at Denver meeting.

Westby, G. H., and Scherbatskoy, S. A., 1940, Well logging by radioactivity: Oil and Gas Journal, v. 38, n. 41, 62.

Widmyer, R. H., and Wood, G. M., 1957, Evaluation of porosity derivation from neutron logs: J. Pet. Tech., p. 57.

Youmans, Arthur, and Buck, John H., 1957, Chemical assay of formation materials by neutron logging techniques: A.C.S., Div. of Pet. Chem. Symposia, v. 2, n. 2, p. 23.

——— Hopkinson, Eric C., and Stewart, Richard M., 1959, D.T. neutron activation logging: paper presented at fall meeting of Society of Petroleum Engineers of the A.I.M.E. held in Dallas, Texas.

——— and Zimmerman, C. W., Recent advances in the use of nuclear physics in oil well surveys: Fifth World Petroleum Congress, Section X, paper 17.

GEOPHYSICS, VOL. XXV, NO. 4 (AUGUST, 1960), PP. 891–904, 9 FIGS.

DENSITY LOGGING*

J. J. PICKELL† AND J. G. HEACOCK‡

ABSTRACT

This review of density logging is primarily a compilation of information presented in the petroleum industry literature. It includes a brief discussion of some of the theory involved in gamma-ray density logging, various calibration curves, comparisons of density-log and core data, and comments on density-log interpretation.

Conclusions are that the density log, under good borehole conditions, provides an accurate means for measuring bulk density of the formation adjacent to the borehole. If grain density is known, valid estimates of porosity can also be made.

Because of the response characteristics of the system, accuracy in determining porosity is best when formation densities are low and porosities are high.

THEORY

The physical phenomena of gamma-ray scattering and absorption as a function of bulk density of environment are utilized in density logging. The method involves measuring the "transmissibility" of a portion of the formation adjacent to the well bore to gamma rays; this is done by bombarding the formation with gamma rays and measuring the intensity of back-scattered radiation a short distance away. With appropriate spacings, energy levels of source and detectors, and collimation techniques, an accurate correlation can be obtained between back-scattered gamma-ray intensity and formation bulk density.

In order to provide some background for the discussions to follow, two concepts of atomic physics—radioactive decay and some reactions of gamma rays with matter—are cursorily reviewed.

Radioactive Decay

It has been found experimentally that the radioactive disintegration of nuclei is exponential in nature. If γ_0 is the initial rate of decay, then the rate of decay at any later time t can be expressed as follows:

$$\gamma_t = \gamma_0 e^{-\lambda t}, \tag{1}$$

where λ is called the disintegration constant or decay constant. This constant is characteristic of the nucleus.

Since each disintegration results in the emission of the same number of products, such as gamma rays, equation (1) also expresses the rate of gamma-ray emission. The time for γ_t to change to $\gamma_t/2$ is called the half-life $-t_{1/2}$ of the nucleus, and from equation (1) we find that

* Shell Development Company, Exploration and Production Research Division (Publication No. 233). Manuscript received by the Editor April 20, 1960.

† Shell Development Company, Houston 1, Texas.

‡ Shell Oil Company, New Orleans, Louisiana.

$$t_{1/2} = \frac{\ln 2.0}{\lambda} . \tag{2}$$

Interactions between Gamma Rays and Matter

Gamma rays are highly penetrating electromagnetic radiation, not deviable by magnetic or electrostatic fields; they are similar to X-rays but are of nuclear origin. The predominant range of energy levels of gamma rays emitted from commonly used density-log sources is from 0.6 to 1.3 Mev.[1]

A number of interactions may occur between gamma rays and atoms of which matter is composed. For the energy levels involved in density logging and the elements most comonly encountered in sedimentary rock, Compton scattering and photoelectric absorption predominate. Compton scattering results when a gamma ray collides with an electron and recoils, usually in some direction other than the incident path. As a result of this collision, the incident gamma ray loses a portion of its energy to the electron. The frequency of Compton scattering which occurs when a stream of gamma rays passes through a material is proportional to the electron density. For a material of atomic number Z, atomic weight A, and density ρ, the number of electrons per unit volume is equal to $N(Z/A)\rho$, where N is the number of atoms per gram atomic weight (Avogadro's number). For light elements such as those likely to be encountered in formation logging (hydrogen excepted), Z/A closely approximates a constant, 0.5; thus the degree of Compton scattering is primarily a function of the density of the material.

The second process, which normally is of only secondary importance, is photoelectric absorption. As gamma rays lose their energy from scattering, they become subject to photoelectric absorption, in which the gamma ray collides with an atomic electron and disappears. The electron is ejected from its nuclear orbit. The process is likely to occur for gamma-ray energy levels less than 0.5 Mev and for material with larger values of Z than are normally found in well logging.

A third process involved in density logging is pair production; however, this is not believed to be important under most conditions because of the high energy level at which this process commonly occurs.

We can schematically envisage the physical processes of density logging as follows: A stream of gamma rays is directed toward the formation. As the gamma rays pass through the rock, some are scattered away or absorbed and never reach the detector; however, others are scattered into the detector, where they are counted. The source-detector arrangement for density logging is such that the greater the degree of Compton scattering and absorption to which these gamma rays are subjected (hence the higher the density of the formation), the lower the response at the detector. The relationship between gamma rays received at the detector and the density of the material is approximately an exponential one.

[1] Mev-1 million electron volts; 1 electron volt is the energy gained by an electron falling through a potential difference of 1 volt. 1 ev = 1.6021×10^{-12} ergs.

This can be derived by the following simplified model. Consider the rate of gamma rays γ_x arriving at a small target area at a distance x away from a source emitting gamma rays at constant rate γ_s. We know that scattering will result in deflecting some gamma rays away from the target, and since the amount of scattering is a direct function of the number of electrons between source and detector, i.e., the amount and the density ρ of the material, we can write

$$d\gamma = -c\rho\gamma dx.$$

Solving, we find

$$\int_{\gamma_s}^{\gamma_x} \frac{d\gamma}{\gamma} = -c\rho \int_0^x dx$$

$$\ln \frac{\gamma_x}{\gamma_s} = -c\rho x,$$

or

$$\gamma_x = \gamma_s e^{-c\rho x}.$$

That is, the counting rate at the target is directly proportional to the source strength, and where the average source-to-target path x is fixed, the counting rate at the target is proportional to $e^{-c\rho}$. In practice, this relationship very nearly holds, with slight deviations attributed to multiple Compton scatterings (where the gamma ray is scattered more than once, first away from the target but subsequently back towards the target) or to interactions other than Compton scattering.

TOOL DESIGN AND INSTRUMENTATION

Two types of density logs are generally available at present, the densilog run by Lane Wells Company and the density log of McCullough Tool Company. Other companies have similar tools available on a limited basis.

The Lane Wells log, Figure 1, utilizes a cobalt-60 source which yields gamma rays having energies approximately of 1.1 Mev and 1.3 Mev and which has a half-life of about 5.2 years. The source is shielded to deflect radiation more or less radially into the portion of the formation adjacent to the tool. A Geiger Mueller detector system, shielded to receive primarily radiation from the formation, is used, with a source-to-detector distance of about 20 inches. Depth of investigation is reportedly about 6 inches beyond the sonde wall; that is to say, about 90 percent of the response is due to material within 6 inches of the sonde wall.

The Geiger counter has several advantages for this work, the most important being that it is stable under elevated temperatures. This type detector is unable to differentiate between high- and low-energy gamma rays, all giving the same response.

The McCullough log, Figure 2, utilizes a cesium-137 source emitting gamma

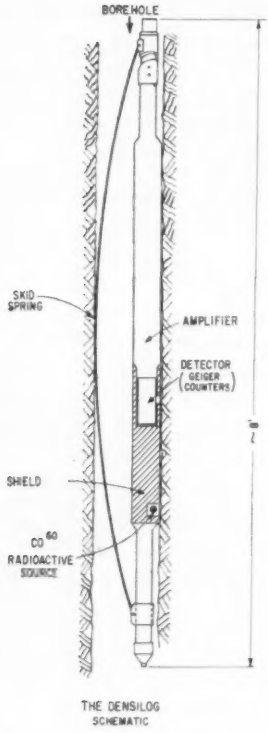


FIG. 1. The densilog-schematic.

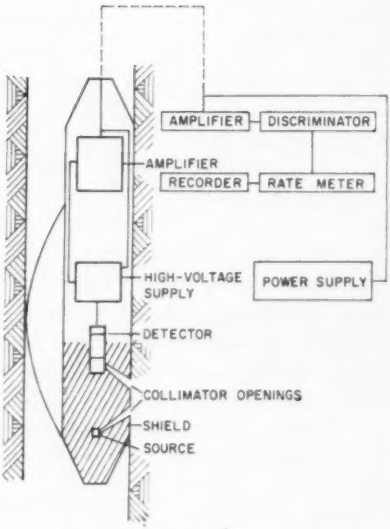


FIG. 2. McCullough density tool-schematic.

rays of about 0.6 Mev in a collimated beam and a scintillation crystal with collimated window as a detector. The source decays with a half-life of about 30 years. The detector is capable of differentiating between gamma rays of various energy levels, and this feature is utilized so that the detector will respond only to the energy band found experimentally to correspond to the deepest penetrating rays possible. Depth of investigation is about 6 inches for the tools now in use. Although the scintillation crystal detector has many advantages, it is subject to temperature effects, and precautions must be taken to avoid overheating of the tool. The scintillation counter has a counting efficiency of 10 to 100 times greater than that of the geiger counter, depending upon the energy level of the gamma rays being counted. Both counters, however, appear to be adequate for density logging purposes.

Both devices utilize a belly-spring arrangement to force the sonde against the side of the borehole in order to minimize the influence of the mud-filled hole on the density readings.

CALIBRATION

The tools were originally calibrated in test pits containing blocks of material with various known bulk densities and with boreholes of several different diameters. These calibration data, Figures 3 and 4, form the basis for relating log response to formation density.[2] Several calibration curves are available for the Lane-Wells log showing response for various borehole diameters and mud weights. The McCullough tool response is relatively independent of borehole

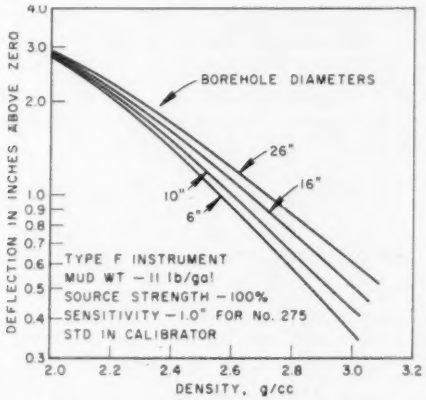


FIG. 3*a*. Lane-Wells densilog calibration for 11-lb/gal mud in borehole.

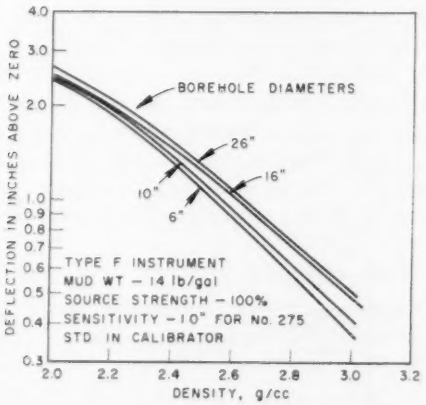


FIG. 3*b*. Lane-Wells densilog calibration for 14-lb/gal mud in borehole.

[2] These calibration curves are for particular models of density logging tools and may not apply to all models. It is important that the calibration data be used which apply to the tool used.

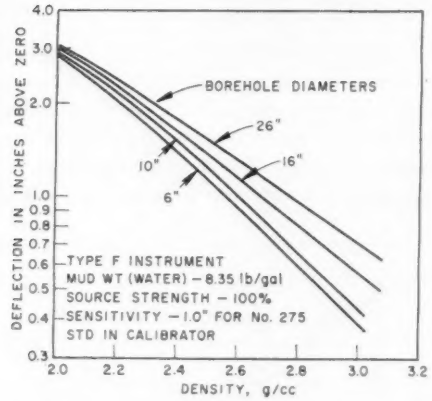


FIG. 3c. Lane-Wells densilog calibration for water-filled borehole.

size (for commonly used bit diameters) and mud weight; hence, only one curve is used. For normal hole sizes (6 to 10 inches), the densilog also requires very little correction for hole size, as can be seen on Figure 3.

In order to standardize field logs for use with the experimental curves, the response of the tool in the field must be related to the response of the tool during the original calibration runs. Both the detector sensitivity and the source strength must be standardized. Two techniques for doing this are (1) by measuring the detector sensitivity with a standard source and calculating the logging source strength from decay curves (equation 1), and (2) by combination checking the source and detector in an environment of known response. The latter technique is considerably more reliable than the former because all components of the logging system are calibrated simultaneously, allowing no room for errors due to faulty source positioning, incorrect source strengths, etc.

When the above standardization techniques are used, it is possible to record density logs which can be directly related to the original calibration runs and thus to the bulk density of the formation. For example, if an environmental

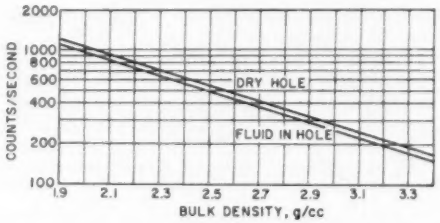


FIG. 4. McCullough density tool, log-calibration curve.

check of the log run in the test pits indicated a counting rate of X counts per second, and a later check made prior to a field run with the same environmental calibrator indicated a counting rate of $0.7X$ cps, then the readings taken during logging should be multiplied by a factor of $1/0.7$ to obtain readings for use with the curves of calibration log response vs bulk density.

FIELD PROCEDURES

In the field, calibrations should be made before and after logging, and overlap sections should be recorded to insure that stable readings are being obtained.

Since radioactivity processes are statistical in nature, there will always be some variation of counting rate with time in a given environment. This variation results in more erratic readings if time of averaging is short than if it is long. The gamma-ray counting devices used in density logging essentially "remember" the number of counts produced for a short period of time which is proportional to the time constant of the circuitry. Hence, statistical variation can be decreased by increasing the time constant. However, an increase in the time constant necessitates slower logging speed in order to maintain good bed-boundary definition.[3] Increases in the time constant also have increasingly less effect on reducing statistical variation as the time constant becomes larger. Therefore, it is necessary to compromise in order to obtain the best statistical variation consistent with reasonable logging speed.

Under some conditions, calibration checks can be obtained in the hole from zones where bulk densities are accurately known, e.g., coal beds, salt beds, anhydrite zones, and greatly enlarged portions of the hole where measured density should approach that of the mud. These checks should be based on experience in the locality and often are very helpful as an indication of the accuracy of the log.

SOURCES OF ERROR

Even with the log accurately calibrated, other factors exist which can lead to erroneous interpretations. Some of these potential sources of error and their magnitude are briefly discussed below:

Borehole Roughness

The major source of error in density log densities is the presence of relatively low density mud interposed between the instrument and the formation in rough portions of the borehole. When the instrument is against the borehole wall, the principal path for the radiation from the source to the detector is through the

[3] Only about 66 percent of the true deflection across a bed boundary is recorded in one time constant; hence, only 66 percent of the change in deflection is recorded in the distance logged during one time constant. As a rule of thumb, about three time constant intervals are needed to record 95 percent of full deflection; therefore, logging speed should be such that the minimum bed thickness to be analyzed will be traversed in more than three time constants.

formation; hence, response is influenced primarily by the formation. When mud is interposed, the radiation path can be either through the mud alone or through both mud and formation, and the drilling fluid greatly influences the response. The amount of this influence increases as the distance of the sonde from the well bore increases and in proportion to the difference in density between the mud and the formation. In other words, for a given degree of roughness, the density log is more influenced by mud opposite dense formations than by mud opposite high-porosity formations, and the effect with high-density mud is usually less than that with low-density mud.

Figure 5 presents a comparison of two logs run over the same cored interval before and after caving has occurred. The densilog deflection follows the core-bulk-density profile very closely for the first run taken where the hole was to gauge but gives erroneous readings after the hole caved. It must be concluded on the basis of many data that density log densities cannot be considered reliable in caved or rough holes, although instances are available where good contact was apparently made with irregular hole geometry. Fortunately, most productive zones tend to be to gauge at the time of logging.

Needless to say, if any doubt as to hole size exists, a caliper survey must be available for effective evaluation with the density log.

Natural Gamma Radiation

The effect of natural gamma radiation on the density log response is reportedly nil, less than 2 percent in shales. Natural radiation effects become increasingly important as source strengths decay. However, logging companies take

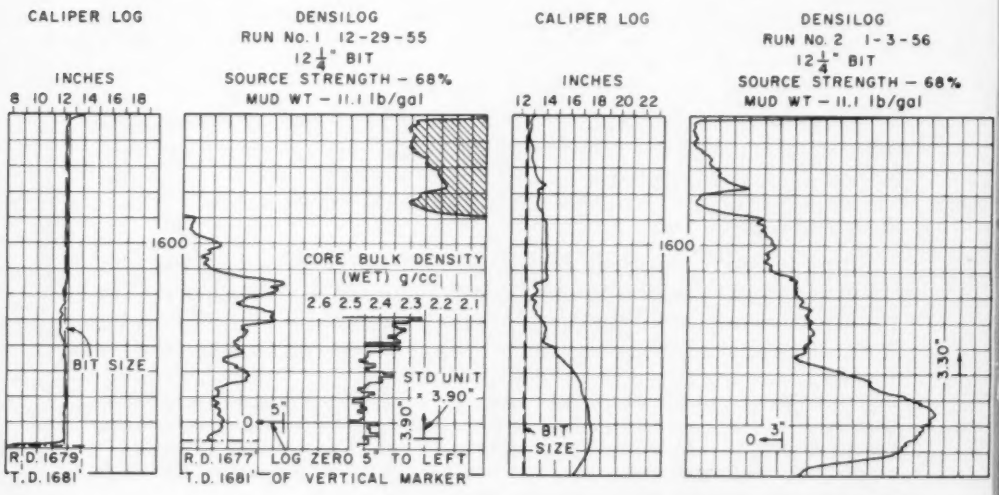


FIG. 5. Effect of poor borehole wall-sonde contact.

care to utilize sources of sufficiently high strength to dominate natural gamma radiation influence.

Ratio of Atomic Number to Atomic Weight (Z/A)

For ideal interpretation, all formations being considered must have the same Z/A ratio as that of the rock used in the original calibration runs. A Z/A ratio of 0.5 has been assumed for the calibrating material in Table 1, which lists corrections for determining bulk densities of materials deviating from this ratio. However, the calibrating materials were not of fixed Z/A, and their Z/A data have not been published; therefore, it is not possible to make these corrections. Fortunately, the effects are not large, as can be seen from Table 1, and errors due to Z/A differences are probably not significant in most situations.

Logging Speed

Maximum logging speeds of about 25 ft per minute are recommended for density logging, because experience has shown that higher speeds often result in losing contact between the sonde and the formation owing to skipping over rough spots. Aside from mechanically induced noise, the upper limit of logging speed is determined by the time constant being used and the thin-bed resolution desired.

Mud Cake

This parameter is difficult to account for because (1) the thickness of the mud cake between the sonde and the formation is not accurately known, and (2) very

TABLE 1

LITHOLOGY CORRECTION FOR Z/A RATIO

		Z/A	Mineral Density, g/cc	Correction* for 100 Percent of Mineral, g/cc
Minerals	Quartz	1/2.003	2.66	+0.005
	Calcite	1/2.0018	2.711	+0.002
	Dolomite	1/2.0046	2.85	+0.007
	Gypsum	1/1.9566	2.32	−0.052
	Anhydrite	1/2.0021	2.957	+0.003
	Salt	1/2.0876	2.165	+0.091
	Feldspars	1/2.0170	2.56	+0.022
		1/2.0173	2.61 –2.64	
	Pyrite	1/2.0687	4.95 –5.17	+0.168
	Water	1/1.8016	1.00	−0.110
	Limonite	1/2.0519	3.51 –3.90	+0.095
	Biotite	1/2.0289	2.652–3.115	+0.041
Clay Minerals	Illite	1/2.0117	2.76 –3.0	+0.016
	Kaolinite	1/1.9859	2.60 –2.68	
	Chlorite	1/1.9853	2.60 –2.96	−0.019
	Montmorillonite	1/1.9751	2.2 –2.70+	−0.030
	Typical Crude Oil	1/1.7979	0.88	−0.100

* With assumed Z/A ratio of 0.5 for calibrating material.

few data are available for estimating the correction if the thickness were known. If the mud cake is not thick, say $\frac{1}{4}$ inch or less, and its density is not too dissimilar from that of the formation, its effects should not be severe and can probably be neglected. However, caution should be exercised in interpreting density log readings from zones with thick mud cakes and/or high densities compared to mud-cake density.

Formation Fluid Content

Under normal conditions (drilling with mud), permeable formations investigated by the density log will probably be invaded by drilling fluid or its filtrate. Figure 6 illustrates the effect of various interstitial fluids on the densities of a typical sandstone and a typical carbonate. The figure also indicates the effect of 100-percent air saturation at various pressures, which should also closely approximate the effects of a typical gas (after weighting for relative saturation of gas and water). In bulk density estimations for formations containing other than fresh water, some correction can be made by utilizing these charts.

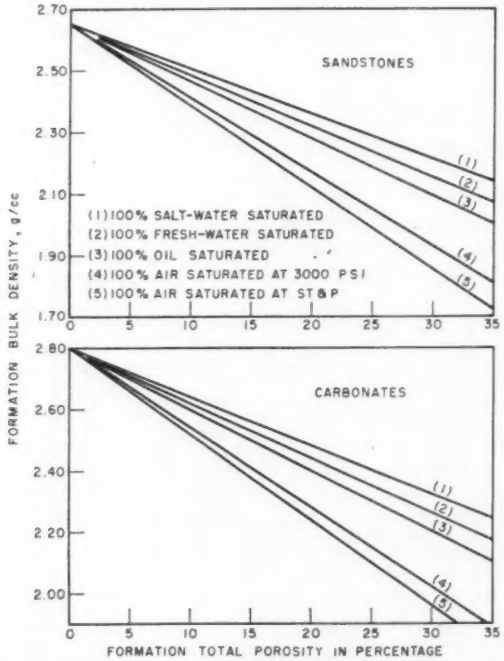


FIG. 6. Variation of formation bulk density with fluid content for sandstones and carbonates.

INTERPRETATION

Bulk Density

Formation bulk densities are obtained directly from the appropriate calibration curves supplied by the service companies. If the borehole is rough, a smoothing technique should be used to arrive at the most representative density log readings. Smoothed curves should be based primarily on the high-density portions of the curve and should lie to the left of the low-density portions, because errors introduced by irregular boreholes are in the direction of low density. Figure 7 illustrates the application of a smoothing technique. It should be emphasized that smoothing is nothing more than a guess, probably in the right direction; however, the only reliable readings are those taken where the hole is to gauge.

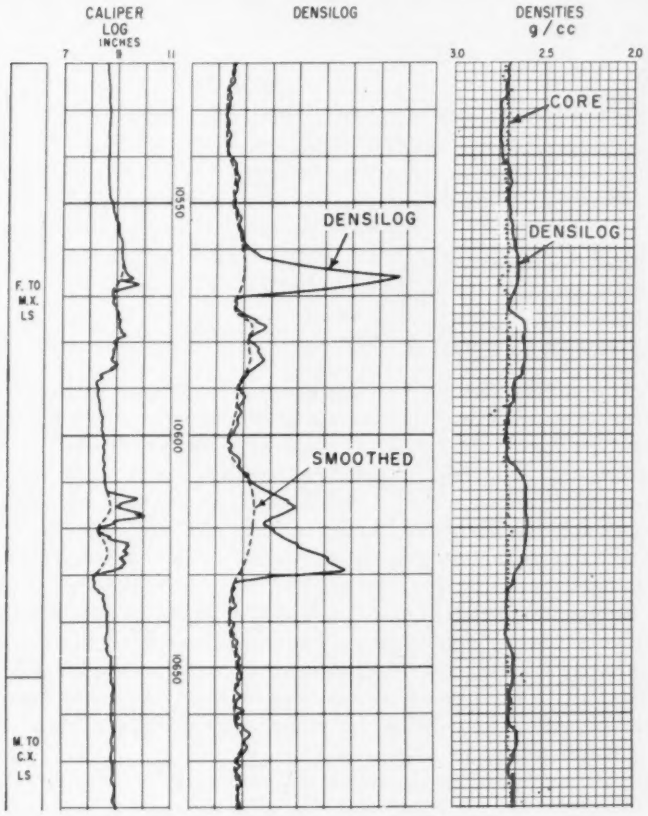


FIG. 7. Densilog vs core density illustrating smoothing.

The accuracy of the density log can be appraised only by comparing its results with known densities. Core densities from wells are not necessarily an absolute standard for a number of reasons: (1) Laboratory results vary for different measuring techniques and are subject to the usual limiting laboratory accuracies. (2) Pressure and temperature changes will probably result in changes of sample density from in-situ to laboratory conditions.

At the present time, however, core data provide the only basis for comparison. A statistical study of bulk densities determined from core analyses and from density logs for several wells indicated an average deviation of ± 0.03 g/cc and a maximum deviation of 0.05 g/cc. These data were from $12\frac{1}{4}$-inch and $8\frac{3}{4}$-inch holes, smooth and to gauge, and included a fairly large range of densities (from 2.26 to 2.75 g/cc). Other authors have reported that the difference between average log-derived and measured core densities rarely exceeds 0.04 g/cc ,where good hole conditions exist.

Porosity

The following relationship is used to derive porosity from bulk density:

$$\phi = \frac{\rho_s - \rho_b}{\rho_s - \rho_l}, \tag{3}$$

where

ϕ = fractional porosity
ρ_s = grain density
ρ_b = bulk density
ρ_l = density of fluid in pores.

Thus, we can see that the reliability of any porosity estimate from the density log is dependent not only on the accuracy of the density-log bulk density but also on the accuracy with which we know grain and fluid densities.

In most cases, fluid density is likely to be rather constant and approximately equal to that of the mud filtrate. Grain densities may vary widely (Table 1), and it is important that the values for zones being analyzed be accurately known. Figure 8 illustrates the wide changes in porosity predicted from equation (3) for small changes in grain density. Analysis of ditch cuttings and cores provides good means for determining grain densities, and this should be done for all zones of interest whenever any doubt exists. It has been observed that the grain densities of shaly sands often show little variation over a fairly large range of shaliness and differ but slightly from clean sands; under these conditions, the density log therefore provides a good means for solving the otherwise difficult problem of porosity determination in shaly sands.

Figure 9 illustrates the agreement obtained between core-analysis porosity and that calculated from the density log with calibration data supplied by the service companies. Each point represents an average of 5 or more ft of core data

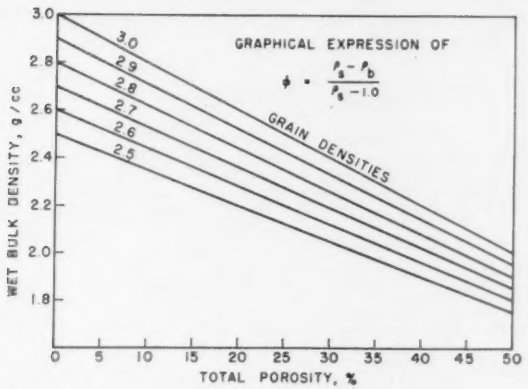


FIG. 8. Wet bulk density vs porosity for various grain densities.

and density log data. Boreholes were to gauge and ranged from $12\frac{1}{4}$ to $8\frac{5}{8}$ inches in diameter. The figure indicates that about 80 percent of the data agree within 2 porosity percent, and best agreement is observed at porosity levels greater than 8 percent. This is consistent with the bulk-density accuracy mentioned previously. The density log is likely to be most accurate at high-porosity levels because (1) the response is most sensitive at low densities, (2) borehole and mudcake effects are minimized where formation density approaches that of the mud,

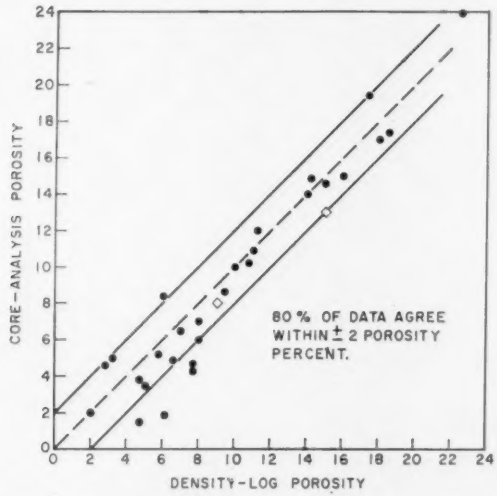


FIG. 9. Density-log porosity vs core-analysis porosity for sandstones and carbonates.

and (3) a given error in grain density results in much greater errors at low-porosity levels than at high-porosity levels.

OTHER APPLICATIONS

Adaptations of density-logging principles can be used to measure fluid density in well bores, to locate cement tops behind casing, to locate water-LPG interfaces behind casing in storage wells, and to locate gas-fluid interfaces in formations under certain conditions. The density log is often helpful in identifying rock types where an independent measurement of porosity is available.

ACKNOWLEDGEMENT

The writers are indebted to Mr. A. L. Bordula, who compiled much of the well data presented in this paper.

REFERENCES

Baker, P. E., 1957. Density logging with gamma rays: Trans. AIME, v. 210, p. 289–294.

Campbell, John L. P., and Wilson, John L., 1958, Density logging in the Gulf Coast area: J. Petroleum Tech., v. 10, p. 7, 21–25.

Edwards, J. M., 1959, Quantitative evaluation of the density log in the Rocky Mountain area: J. Petroleum Tech., v. 11, p. 29–34.

Werner, H. J., Bennett, A. D., Monaghan, Ralph, 1957, Geologic use of the densilog: paper presented at Mid-Continent regional meeting of AAPG, Oct. 31–Nov. 1, 1957.

Zak, Albin, J., and Smith, Joe Ed, Gamma ray density logging: AIME, preprint no. 1253-G.

GEOPHYSICS, VOL. XXV, NO. 4 (AUGUST, 1960), PP. 905–927, 19 FIGS.

PRODUCTION WELL LOGGING TECHNIQUES*

HARVEY L. BRYANT†

ABSTRACT

Production well logging techniques provide information necessary for efficient and economical well production. The various techniques are summarized and grouped into the three phases of well production. Temperature logs, radioactive tracer logs and velocity logs are used to obtain cement tops and indications of cement channeling in well completion work. In well repair work encroaching gas and water may be located by various neutron logging techniques, the temperature log, the flowing fluid density log, the gamma-gamma log and the conductivity log. Well evaluation work, including fracture location, injectivity profiles and productivity profiles can be facilitated by use of radioactive tracer logs and the flowmeter log.

Field examples are presented to demonstrate usage of the many logging techniques. Interesting applications of the flowing neutron log are shown including multiple gas-oil contact location, gas "coning" and dual completion logging operations. Location of water entry by the flowing fluid density log and the conductivity log are illustrated.

The "Humble" flowmeter is briefly discussed. Future development trends in the field of production well logging conclude the paper.

INTRODUCTION

Production well logging techniques provide inside and behind the pipe evaluation of the borehole conditions and formation characteristics necessary for efficient and economical well production. A production well logging process may be carried out immediately after a well is drilled and cased or at some time after a well has been produced. All production well logging techniques have as their objective the provision of information which will allow successful well production.

Many of the logging processes to be included here under production well logging techniques are not new and have been publicized in service company literature, trade journals, and professional journals. However, some of the techniques and several of the logging processes to be discussed are new and may not have received widespread publicity.

Specifically, production well logging techniques can be divided into three groups:

1. Logging processes used in well completion work to facilitate bringing a potential oil well into primary production.
2. Logging processes used to effect well repairs.
3. Logging processes used in well evaluation.

WELL COMPLETION WORK

Once a borehole has been drilled, open-hole surveys taken, and casing cemented, further information necessary for the well completion must be obtained.

* Presented at the 29th Annual International Meeting of the Society, Los Angeles, California, November 10, 1959. Manuscript received by the Editor December 4, 1959.

† Creole Petroleum Corporation, Caracas, Venezuela.

Of primary importance is assurance that the cement covers all of the productive zone or zones and prevents behind the pipe communication with water bearing zones. Multiple zone completions make behind the pipe communication undesirable for a different reason, the prevention of reservoir communication. Finally, if a productive interval is thin or if the well is to be a multiple zone completion, positive depth control is an absolute necessity.

Cement tops may be located by at least four different production logging processes: the temperature log, the gamma-ray log (after radioactive tracer injec-

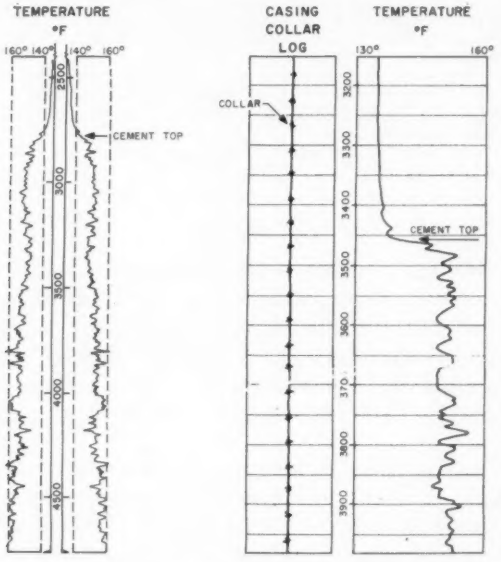


FIG. 1. Cement tops by temperature logs.

tion), the continuous velocity log or sonic log, and the cemoton log. Temperature logs have been in use longer, and are probably still the most widely used. The temperature log delineates the cement top because the cement generates heat as it sets. Figure 1(a) shows a cement top indicated by an increase in temperature at the depth where the cement is present behind the casing. For best results with the cements most commonly used, the log should be run from 12 to 40 hours after cementing. In addition to locating the cement top, a temperature log generally correlates with a caliper log or section gauge and with the electrical log. Correlation of the temperature log and one of the open hole surveys provides positive depth control when the casing collar locator is run with the temperature log, Figure 1(b). Detection of cement channeling with the temperature log is difficult and cannot be considered completely reliable. Pronounced intervals of channeling

may be characterized by anomalous temperature log-borehole configuration correlations.

When a radioactive tracer is injected into the cement during cementing operations, the normal gamma-ray log is altered. Various methods of tracer injection and a variety of radioactive tracers may be used. The best tracers are probably water soluble ones mixed homogeneously throughout the cement. Figure 2(a) is a gamma-ray log obtained in a well where such a tracer was used. The cement top is at the point where the gamma-ray counting rate decreases drastically and the normal formation gamma-ray counting rate resumes. Figure 2(b) shows how the gamma-ray-radioactive tracer log is related to borehole diameter. Increasing

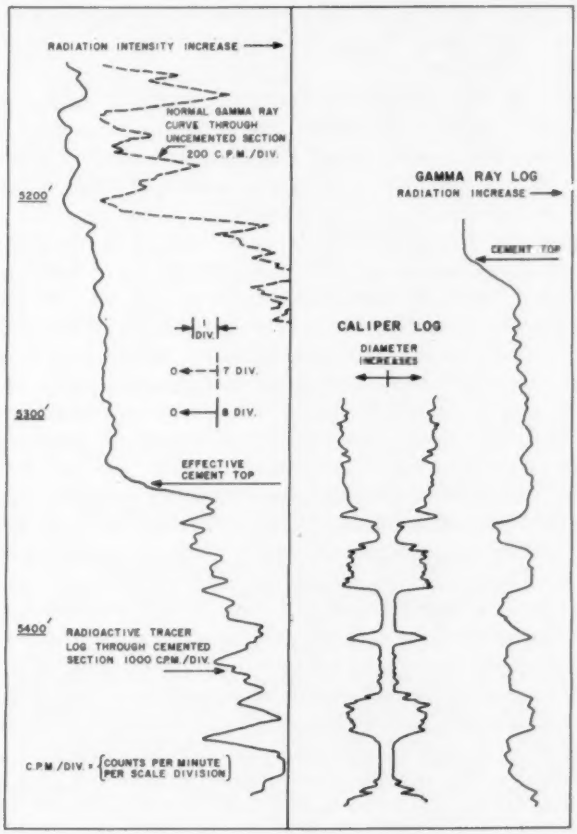


FIG. 2. (a) Gamma-ray log, (b) Cement tops by gamma-ray-radioactive tracer log.

borehole diameter and the resulting greater quantity of radioactive cement are accompanied by increasing gamma-ray intensity. Increase in tracer radiation intensity is not a straight line relationship with borehole diameter but is a logarithmic one. If the casing is centralized, any great difference in correlation between the caliper log and the gamma-ray-radioactive tracer log may indicate channeling. Depth control for subsequent perforating operations is obtained from the casing collator locator which is available with the gamma-ray-radioactive tracer log.

A new technique for locating cement tops is the use of the continuous velocity log or the sonic log. Velocity logs and sonic logs are normally utilized only in the open hole, but in this application they are run in the cased and cemented borehole. This technique was developed in Venezuela and there are still unknowns in the theory and interpretation. Cement tops are reliably indicated and, although the technique is new, many Venezuelan companies feel that cement channeling may often be recognized.

Figure 3(a) shows a generalized two-receiver velocity logging tool and the scheme of acoustic energy transmission and recording in an open hole survey. Figure 3(b) shows how acoustic signals might follow four different travel paths in a cased and cemented borehole: (1) through the mud, (2) through the casing, (3) through the cement sheath, and (4) through the formation. Theoretically, the acoustic signal recorded should take the path resulting in the shortest interval travel time. Since the mud travel time is large and fairly constant at about 200 microseconds/ft, it may be easily eliminated from the log. The metal used in most casing has a much smaller travel time of about 56 microseconds/ft. Travel times in the various cement mixtures vary but are greater than those of casing. The lithologies encountered in a borehole have widely varying travel times ranging from 175 microseconds/ft for some shales to 40 microseconds/ft for some dolomites. Sandstone travel times vary but generally are greater than the 56 microseconds of casing metal. Some limestones have interval travel times as small as 44 microseconds/ft. The signal recorded by a velocity or sonic logger in a cased hole could have been transmitted predominately through the casing, the cement, or the formation. In practice, where there is a good cement bond between the casing and formation, the velocity tool's receiver gain can be adjusted to select and record a signal transmitted predominately through the formation. With proper adjustment, the tool will record best that range of acoustic signal strengths representing cement bonded formation. If the formation is not bonded to the casing by cement, the tool records an acoustic signal resulting from travel through the casing metal. This casing acoustic signal is rather constant in strength and is easily recognized by the resulting characteristic travel time of 56 microseconds/ft. Figures 4(a) and 4(b) show cement tops located by a one-receiver continuous velocity log and a two-receiver sonic log, respectively.

Another new device available for locating cement tops is the cemoton log. To date, the reports of success obtained with this production logging process have

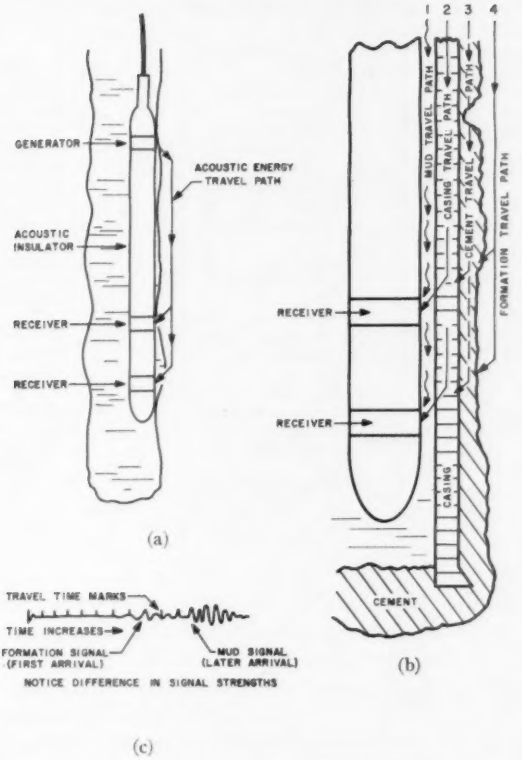


FIG. 3. (a) Two receiver velocity or sonic logger, (b) possible acoustic energy travel paths in cased borehole, (c) enlarged and drafted 35 mm picture of velocity logger oscilloscope.

varied. Also, at this writing, little information is available regarding the operating principles of this new production well logging tool.

WELL REPAIRS

Before a petroleum reservoir is depleted, well remedial work often becomes necessary. Individual well production may suffer from encroaching water, an expanding gas cap, or possibly both. Other factors which may necessitate well repair are break-down of primary cement jobs, casing rupture, holes developed in the casing, break-down of perforations previously squeeze-cemented to shut off water or gas, plugging of liners or perforations and many others. A production well logging technique may provide the information which will allow repair of the well and its subsequent return to economical and efficient production.

TABLE I. PRODUCTION WELL LOGGING TECHNIQUES

A. Well Completion	B. Well Repair	C. Well Evaluation
1. Cement Tops a. Temperature Log b. Gamma Ray-Radioactive Tracer Log c. CVL or Sonic Log d. Cemoton	1. Gas Location a. Temperature Log b. Neutron Log c. Multi-spaced Neutron Log d. "Flowing" Neutron Log e. "Flowing" Fluid Density Log f. Gamma-Gamma Log	1. Productivity Profiles a. Flowmeter Log b. Radioactive Tracer-Metering (with gamma ray counter) c. Spinner Survey
2. Cement Channeling a. Gamma Ray-Radioactive Tracer Log b. CVL or Sonic Log	2. Water Location a. "Flowing" Fluid Density Log b. Conductivity Log c. Gamma-Gamma Log d. Spectral Logs	2. Injectivity Profiles a. Flowmeter Log b. Radioactive Tracer-Metering (with gamma ray counter) c. Spinner survey d. Gamma Ray Radioactive Tracer Log (Permeability Survey)
3. Depth Control a. Casing Collar Locator with other logs	3. Casing and Tubing Leaks a. Temperature Log b. Caliper Log c. Flowmeter Log	3. Fracture Determination and Special Applications a. Gamma Ray-Radioactive Tracer Log
4. Gas Location a. Neutron Log b. Multi-spaced Neutron Log	4. Communication between Productive Zones a. Temperature Log b. Flowmeter Log	

In the location of gas, the production well log analyst has a number of logging devices from which to choose. Reference to Table I shows that, except for the temperature log, these techniques depend on radiation processes. Gas location with the temperature log depends on the cooling effects resulting from gas expansion as it enters the well bore. In a cased borehole the production string arrangement, gas production from more than one zone, and borehole fluid turbulence may prevent successful interpretation of the temperature log.

Three production logging techniques depend on a neutron logging device as a means of locating gas: (1) the neutron log, (2) the multi-spaced neutron log, and (3) the "flowing" neutron log. Two types of neutron logging devices are used to obtain the above mentioned neutron logs. Both logging devices bombard the formation with neutrons from a source commonly consisting of radium and beryllium or polonium and beryllium. The basic difference in the two neutron logging tools is in the recording of the results of the bombardment. One of the neutron logging devices records a secondary gamma ray which is emitted by the atoms of the formation upon capture of the bombarding neutron. This log is called a neutron-gamma curve. The other neutron logging device records the rebounding slow neutron and the log produced is called a neutron-neutron curve. Interpretation of the neutron-gamma curve and the neutron-neutron curve is basically the same. Both logs are measures of the hydrogen content or porosity of the formation. The hydrogen atom, because of its small mass and availability within the pore spaces of the rock, contributes greatly to the efficient slowing down of the bombarding

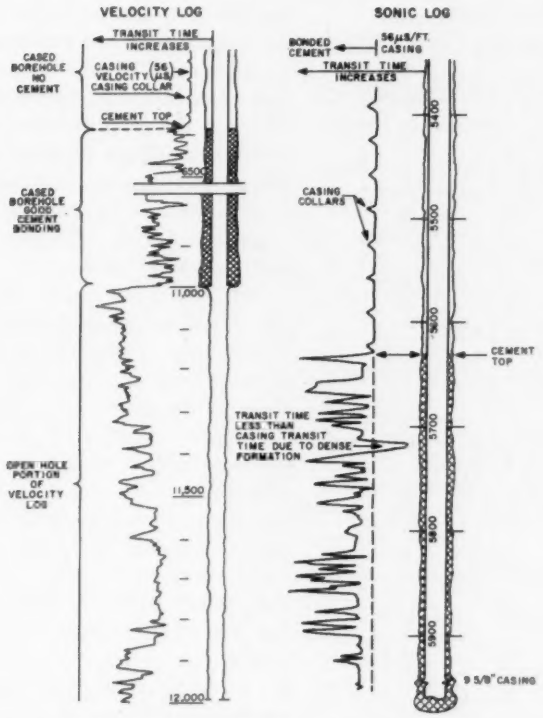


FIG. 4. Cement tops by velocity and sonic logs.

neutrons. Changes in the efficient slowing down of the bombarding neutron cause the neutron log fluctuations which are of interest.

Gas detection by the neutron log is based on the fact that oil and water have virtually the same number of hydrogen atoms per unit volume whereas gas has a much smaller amount. When the formation pore space contains oil or water (high hydrogen content), a low neutron curve response is obtained. A gas zone (low hydrogen content) causes a high neutron curve response. Figure 5 shows some characteristic neutron curve responses and the appearance of a gas-oil contact. Notice, too, how a knowledge of the formation porosity is necessary to differentiate a low porosity sand from a gas sand. Figure 6 shows how the contrast in hydrogen content between gas and oil or water decreases with depth; gas composition is also a factor. The inability of the conventional neutron log to locate gas zones and gas-oil contacts is often related to the well control fluid lost to the formation. In controlling the well and during clean-out, a sheath of well control fluid is created around the borehole. Many times, the bombarding neutrons can-

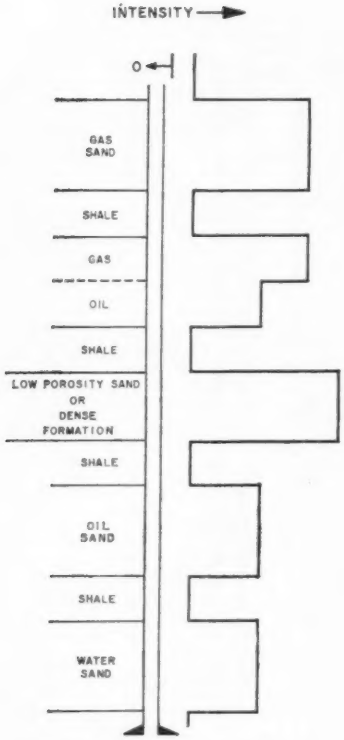


FIG. 5. Neutron curve response.

not efficiently penetrate this sheath of constant high hydrogen content. The multi-spaced neutron log was developed to investigate more efficiently behind this invaded zone into the undisturbed formation. Gas detection by this technique consists of running an additional neutron curve employing a greater source-to-detector spacing. The conventional neutron logging tool can be used to log this second neutron curve, or the service company may supply a modified tool. A reduced logging speed and considerable equipment adjustment is necessary to allow properly for the lower counting rate of the longer spaced neutron curve.

In practice, effective interpretation of the multi-spaced neutron log requires that calibration of the two curves be made in an oil or water sand. Calibration of the two curves consists of obtaining the same change in neutron curve response from the low neutron curve response in a shale to the somewhat higher response in a sand. The neutron zeroes for the two curves do not then coincide, but the change in neutron curve deflection from shale to sand is equal. Interpretation consists of observing the "microlog effect" when the two curves are superimposed. A gas sand is revealed by the positive separation of the two curves, i.e., by the higher neutron curve response of the longer spaced neutron curve, Figure 7. The positive separation is related to the greater effective radius of investigation of the longer spaced neutron curve. The amount of invasion is the most critical factor controlling the success of this technique. Even a moderate depth of invasion may exceed the practical limits of the effective radius of investigation of the longer spaced neutron curve. Uncentralized casing and the possibility of different tool positions in the borehole during the logging of the two curves may cause fluctuations complicating interpretation. Multiple logging runs are of value in reducing purely statistical variations.

If a well is flowing, and if the tubing is unobstructed and large enough to allow passage of the logging tool, a third neutron logging technique may be employed to locate gas. This technique supplies a log called the flowing neutron log, deriving its name from the fact that the well must be flowing. The flowing neutron

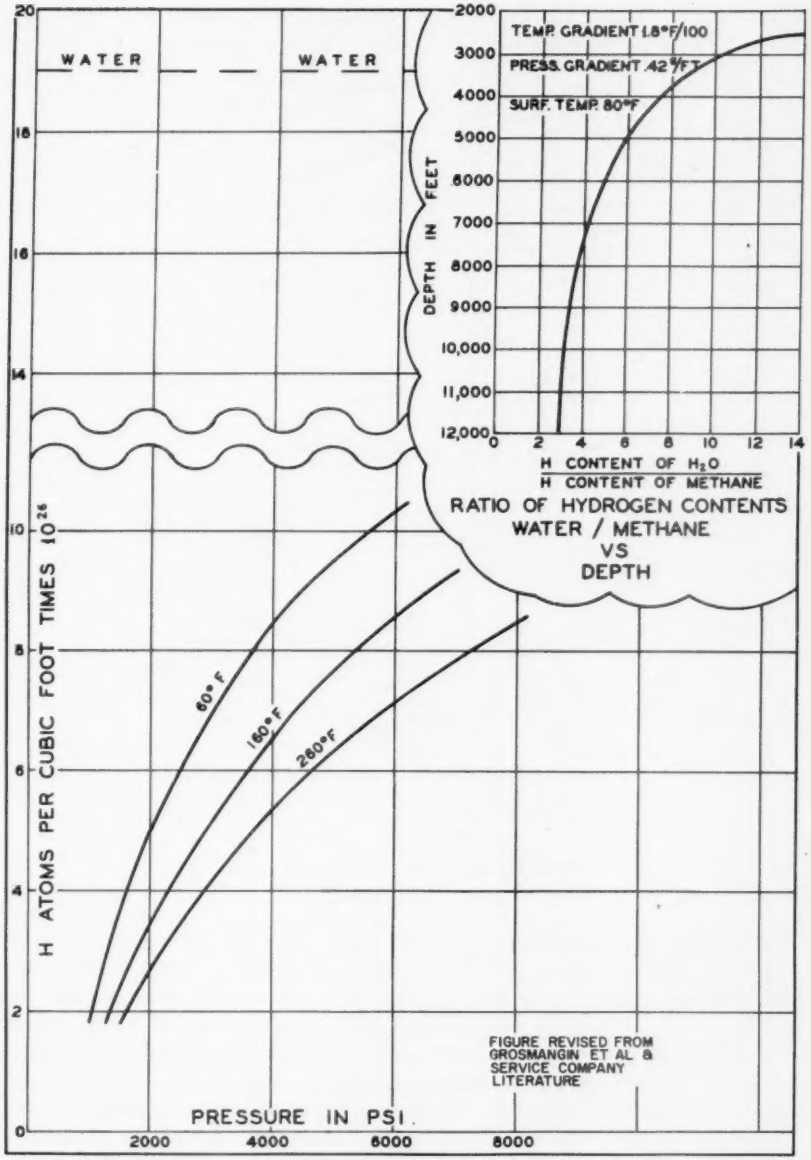


FIG. 6. H Atoms/cubic ft of methane gas vs temperature and pressure.

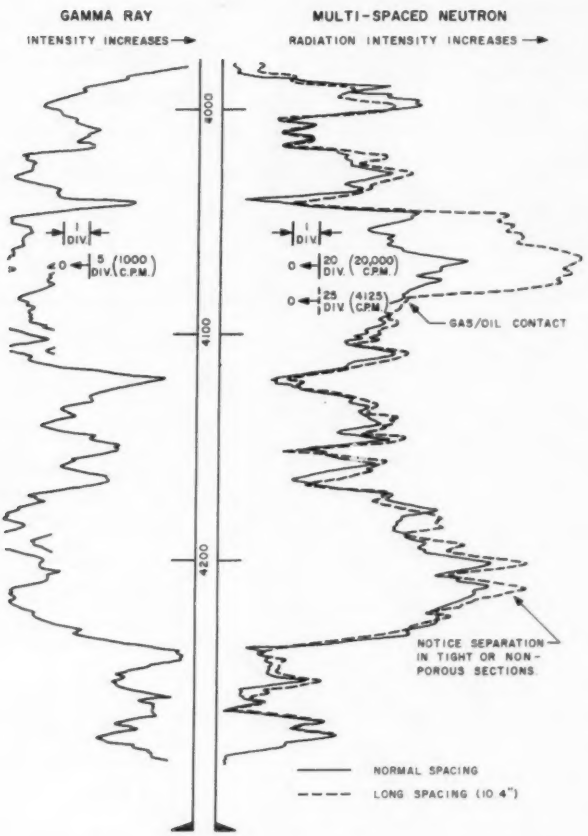


FIG. 7. Gamma ray and multi-spaced neutron.

logging technique capitalizes on the fluid level effect pictured in Figure 8 and plotted in Figure 9. Figure 8 illustrates how casing strings and fluid levels affect the neutron curve response. Figure 9 plots the neutron curve response obtained in two cased holes of different size, water filled and air filled. This sharp increase in neutron curve response above a liquid level is a result of the greatly decreased amount of neutron-absorbing hydrogen present in the gas-filled part of the borehole. Stated slightly differently, the higher radiation intensity recorded above a fluid level is a result of the reduced neutron absorption near the neutron source. Figure 10 combines the effects shown in Figures 8 and 9 and illustrates how a flowing neutron log might look. Figure 11 is an actual field example of a flowing neutron log obtained after the conventional neutron log and the multi-spaced

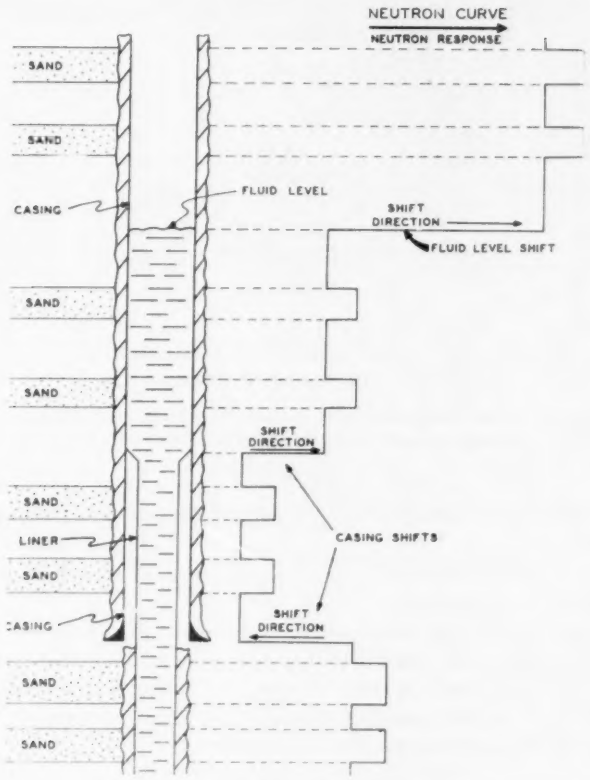


FIG. 8. Borehole effects on the neutron curve.

neutron log failed to locate the gas. Multiple gas-oil contacts may be located by this technique, since each point of gas entry is pin-pointed by a "quasi" fluid level, Figure 12.

Thick sands producing at high flow rates may suffer from gas coning in the vicinity of the borehole. Figure 13 demonstrates how a choke change may allow a repeat run to show gas coning. This figure also demonstrates how a higher gas-oil ratio (dotted curve) results in a higher neutron response. Figure 14 shows this same effect in a plot of gas-oil ratios vs change in neutron response.

Logging operations in dual completions, using the flowing neutron technique, offer some interesting possibilities. Figure 15 is a log obtained through the lower tubing string of a dual completion. Both zones were producing with a high gas-oil ratio, and the flowing neutron log shows two distinct gas-oil contacts. This interpretation was possible even though the tool was inside the lower tubing during the logging of the upper zone.

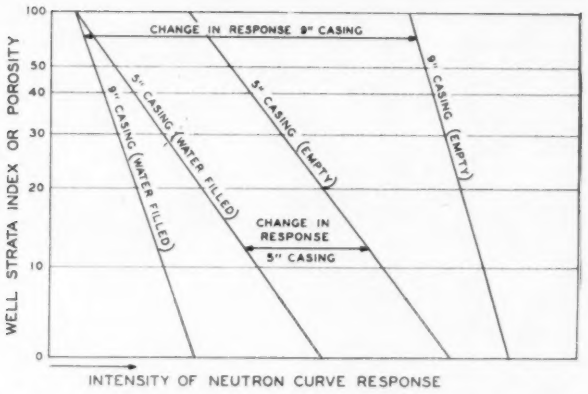


FIG. 9. Neutron conversion chart showing neutron response in water filled and empty hole. Change in neutron response from filled to empty hole is virtually the same for all porosities in a given size hole.

The following well-site procedure has proved successful in obtaining flowing neutron logs:

1. Allow the well to flow until the gas-oil ratio has stabilized before commencing logging operations.
2. Rig up lubricator normally used during perforating operations (Figure 16).
3. Log through-tubing using a $1\frac{3}{4}$-inch or smaller gamma-ray-neutron instrument while the well is actually flowing. A static log may aid interpretation. Sinker bars may be attached to enable the logging instrument to pass to the desired depth against flowing pressure.

Flowing neutron logs have been utilized in Venezuela, Canada, Arabia, and the United States with rather spectacular results. Logs have been obtained under a variety of well-site conditions, including productions up to 2,350 bbl./day, tubing head pressures up to 2,000 psi, and gas-oil ratios as low as 1,600 standard cu-ft/bbl. Table II lists well data and production characteristics of five Venezuelan wells repaired from information obtained by flowing neutron logs.

TABLE II. WELL REPAIR BY FLOWING NEUTRON LOGS

Well	Size Inch	Choke Size Inch		Oil Production bbl/day		Gas/Oil Ratio cu ft/bbl.		Tubing-Head Pressure psi		Depth to Gas
		Before	After	Before	After	Before	After	Before	After	
1	$9\frac{5}{8}$	$1\frac{1}{4}$	$\frac{7}{8}$	2,370	2,202	2,991	653	195	300	3,750
2	5	$\frac{1}{2}$	$\frac{1}{2}$	548	818	3,500	294	330	215	5,030
3	$5\frac{1}{2}$	$\frac{1}{4}$	$\frac{3}{8}$	210	503	6,092	468	660	290	3,400
4	$5\frac{1}{2}$	$\frac{3}{8}$	$\frac{7}{8}$	1,038	2,829	5,904	994	1,100	470	5,028
5	$9\frac{5}{8}$	$\frac{1}{2}$	$\frac{1}{2}$	1,430	717	1,992	560	350	150	3,900

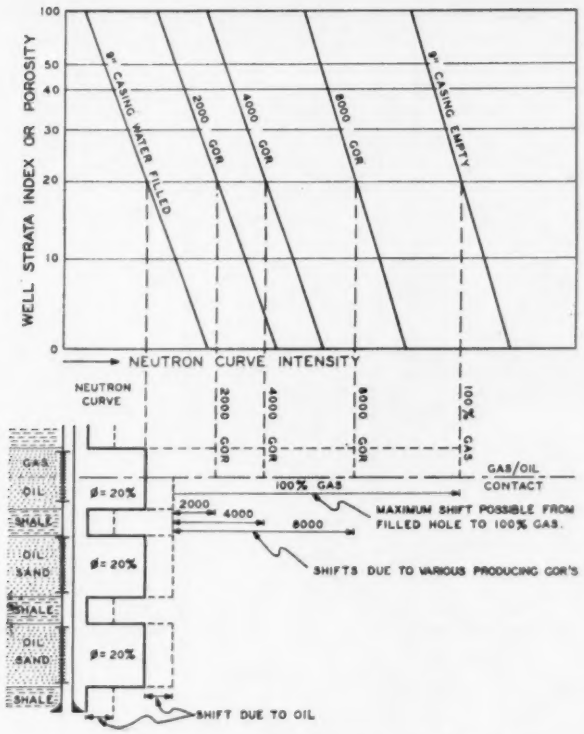


FIG. 10. Neutron conversion chart with speculated neutron curve shift due to various producing GOR's.

Two methods of water location in producing or flowing wells are in the process of development. One is the flowing fluid density logging technique and the other is the conductivity logging technique. Different gamma-ray absorptivities in different density fluids provide the basis for the flowing fluid density logging tool, Figure 17(a). Field experiments on oil wells in Venezuela in early 1957 showed that the contrast in gamma-ray absorptivities between oil and water could be recorded. Laboratory work was also published in 1957 predicting the same results. The principle of the flowing fluid density log is also illustrated in Figure 11. Here, the gamma-ray curve, which was recorded simultaneously with the neutron curve, shows a pronounced shift in the direction of increasing radiation. Part of this shift is a result of back-scattered gamma rays originating at the neutron source (radium-beryllium). The shift in the gamma-ray curve is recorded seven ft higher than that of the neutron curve because the radium beryllium source passed into the zone of gas entry seven ft later than the gamma-ray counter. Figure

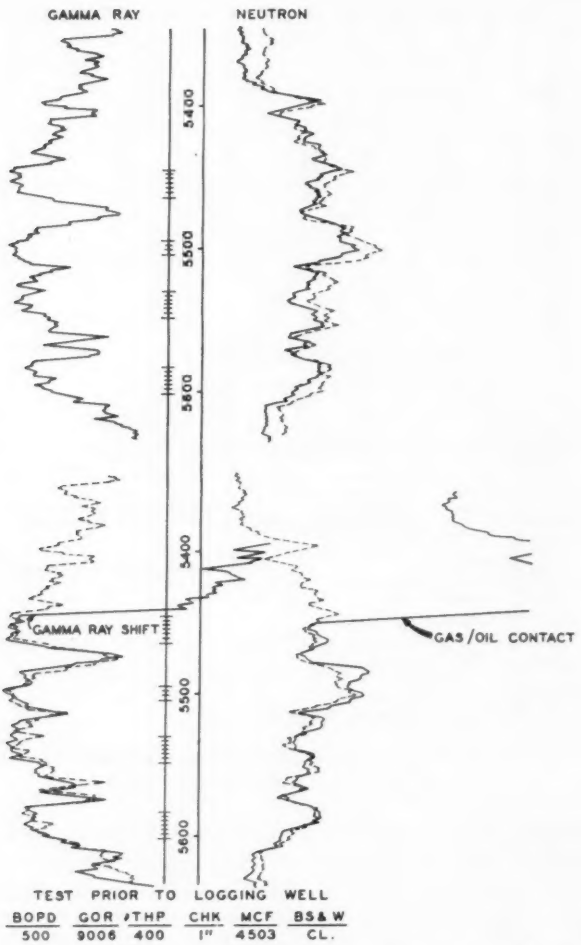


FIG. 11. GR-N Logs—Well Dead (upper). Flowing GR-N Log (lower). Dashed curve in upper illustration is multi-spaced neutron curve. Dashed curve of lower illustration in GR-N log from above. Notice shift in gamma-ray curve is 7 ft higher than neutron curve shift.

17(b) is a successful field example of the flowing fluid density log. A series of logs were used to locate the oil water contact due to some apparent borehole effects. This log was run with the prototype tool which has been improved. The gamma-gamma log is another device which operates on the same principle and has also been used successfully.

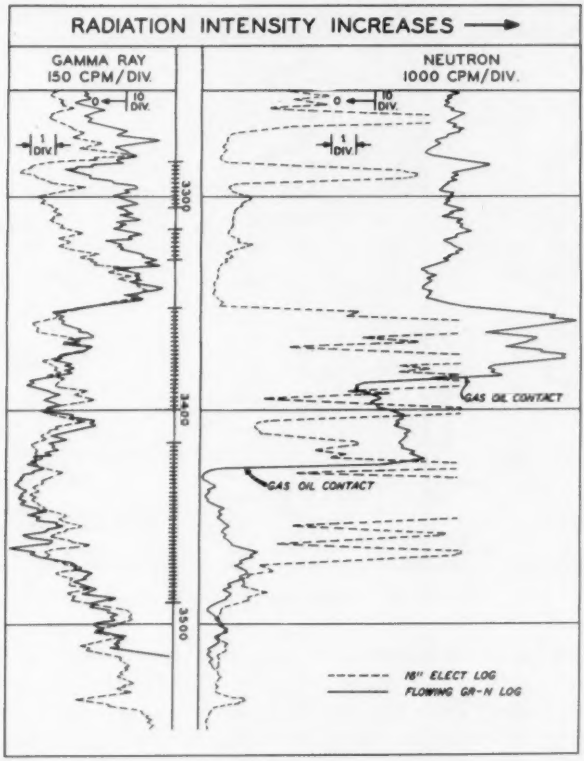


FIG. 12. GOR 3751.

The conductivity log is an electrical method for locating water entry in a flowing well. This device was developed in the United States for work in Venezuela. At this writing a diagram is not available of this logging tool, but it is known to consist of a micro-spaced electrode arrangement. Interpretation of the conductivity log is based on certain considerations of fluid properties and mixture which are not available for publication. Figure 18 shows a series of conductivity logs run in a Venezuelan well to locate water entry. The four logs were run at intervals of 15 minutes, commencing when the well was placed on production. Water entry is apparent at the point where the conductivity suddenly increases. The water entry here was not the result of encroachment (bottom water). A faulty cement job allowed water to enter the well bore via the upper set of perforations from the overlying water-bearing formation. Water analysis and well repair confirmed the information supplied by the conductivity log.

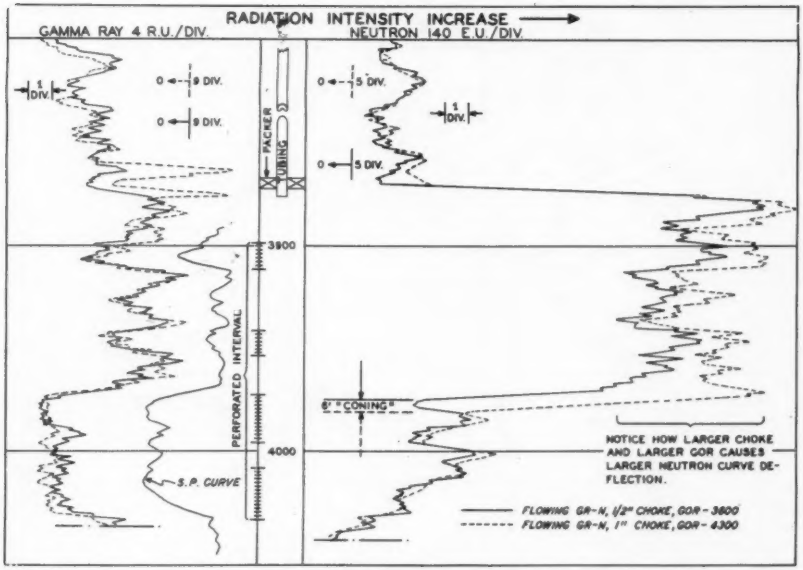


FIG. 13. "Gas Coning" shown by choke changes.

Radiation log discrimination of water bearing zones through casing is now being claimed by most of the logging companies, although these claims have yet to be fully established. These logs have been advertised and commercially offered under a variety of names including: chlorinilog, spectral log, saltilog, salinity log and isotron log. All of these logs are believed to be forms of neutron logging that use conventional neutron sources to obtain a hydrogen response curve and a chlorine response curve. Anomalous separation of the two curves may be indicative of a water bearing formation. Conditions favoring successful application include high porosity, high formation water salinity, little formation invasion, cemented casing, low salinity borehole fluid, low water saturation in the oil or gas zones, and a uniform hole size. Reports on the success of these new radiation techniques have varied.

WELL EVALUATION

The third group of production well logging techniques encompasses those techniques used in evaluating well production. For practical purposes well stimulation and secondary recovery processes are included in this classification. Many fine papers have been published about the production logging techniques used to supply information for well treatment work. Acidizing operations, fracturing operations, etc. are specialized well treatment operations where radioactive tracer

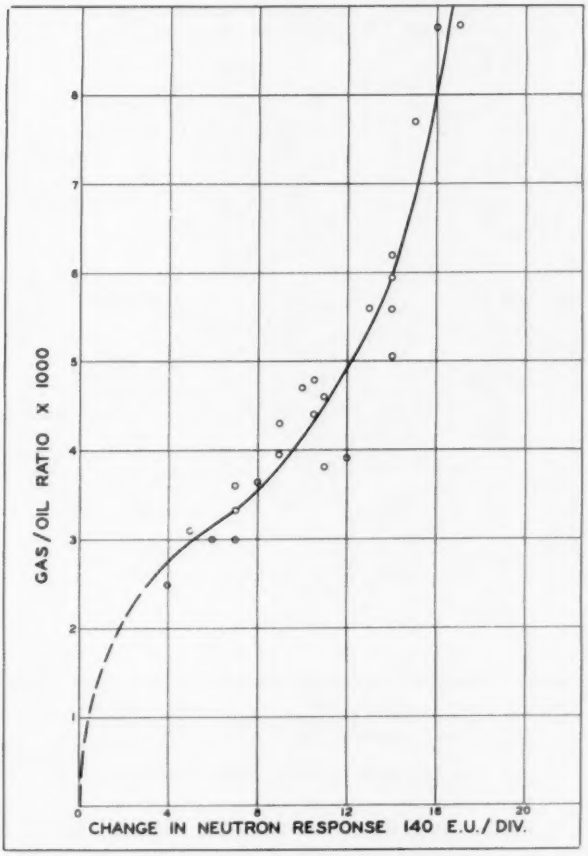
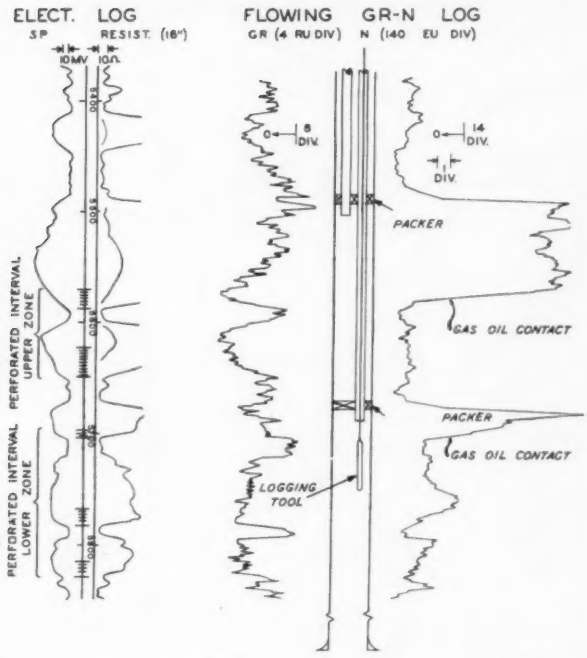


FIG. 14. GOR'S vs change in neutron response. All points plotted are for wells with 5½ inch to 7 inch diameter casing.

logs can supply useful information. Even to summarize the theory and interpretation of those techniques here would be impractical.

The writer feels that the Humble subsurface flowmeter is a major breakthrough in the field of production well logging. Determining borehole flow-rate profiles through tubing has long been a problem demanding solution. The spinner survey for detecting zones of lost circulation, direction of fluid flow, etc., presaged the flowmeter. Now, it would seem that the problem of controlled fluid metering has been solved and the "quantity" has been added to the "quality" of other production logging techniques. Figure 19(a) is a diagram of the device developed



FLOWING NEUTRON LOG OBTAINED BY LOGGING THRU LOWER TUBING STRING

		BOPD	GOR	CHK	THP
UPPER	STRING	1384	4600	1¼	360
LOWER	STRING	1475	1800	1	280

FIG. 15. Gas-Oil Contacts in Dual Completions.

by Humble. Briefly, after inflation of the rubber packer, fluid is directionally metered through the cylindrical chamber where it imparts rotary motion to a spinner. The rotational speed of the spinner is calibrated to measure fluid flow rate. A small single conductor cable serves to transmit the electrical pulse sequence generated by the spinner rotation. Direction of flow can be determined at the surface by the sequence of the electrical pulses. Rate of flow can be determined by the repetition rate of the electrical pulses. Surface electrical control of the rugged rubber packer allows numerous resetting operations. The packer is cheap and expendable but may serve for many profiling operations. Packer seals may be obtained in tubing casing within a range of diameters from $2\frac{1}{2}$ to 7 inches. Flow rate measurement is accomplished where productions range from 10 to 1,000 bbl/day. An idealized version of how an injectivity profile is obtained is pictured in Figure 19(b). Figure 19(c) is a field example of an injectivity profile. This illustration shows how the flowmeter can supply information which can lead to the use

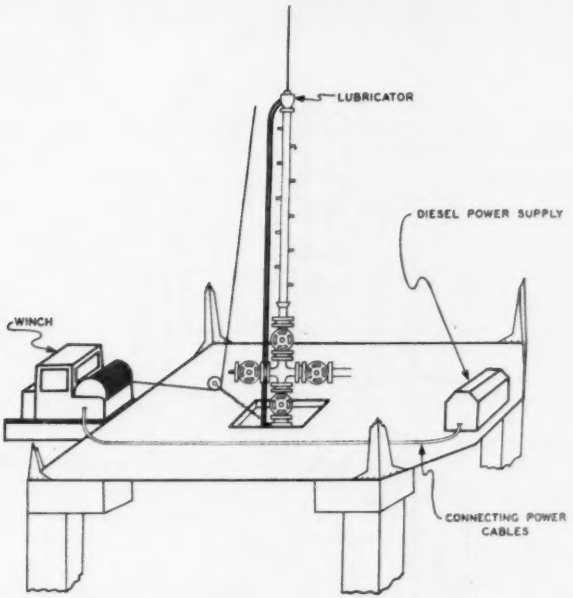


FIG. 16. Equipment Arrangement for Logging Operations.

of more efficient injection rates. Undoubtedly many secondary recovery projects could be more efficiently engineered with this type of well data. Production practices, long considered "fixed" or standard for an area, will be reviewed and revised as a result of flowmeter productivity profiles.

FUTURE DEVELOPMENTS

Substantial savings in rig time, reduction of production and exploitation expenses, and increased recoveries are some of the benefits already realized from new production logging methods. In well repair, the development of the flowing neutron log, flowing fluid density log, gamma-gamma log, and the conductivity log has supplied the need for fluid quality control in flowing wells. Increased emphasis in the field of well stimulation and treatment dictated the need for fluid quantity control and the flowmeter resulted.

Future development will follow trends of specialized needs. Further development of new secondary recovery projects will probably require special production logging techniques. It is still impossible to obtain fluid quality and quantity control in flowing wells on one logging run; work may be directed to this end. The need for a knowledge of borehole conditions in pumping wells may lead to modifications of existing production logging techniques. Demand, then, for specialized

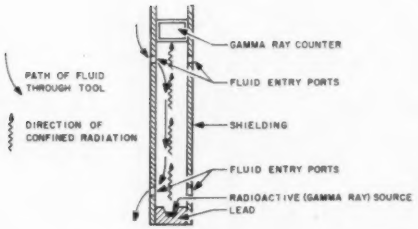


FIG. 17. (a) Fluid Entry Analyzer.

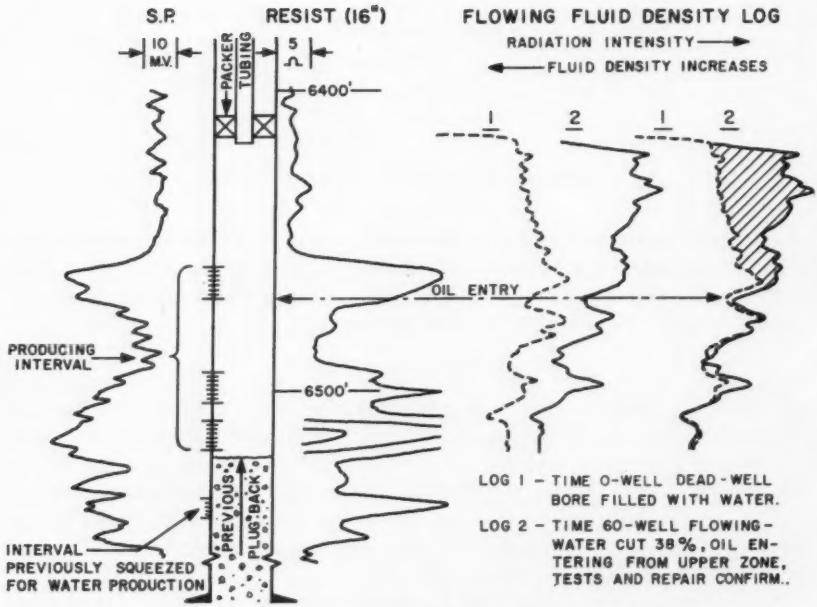


FIG. 17. (b) Flowing fluid density log for water entry.

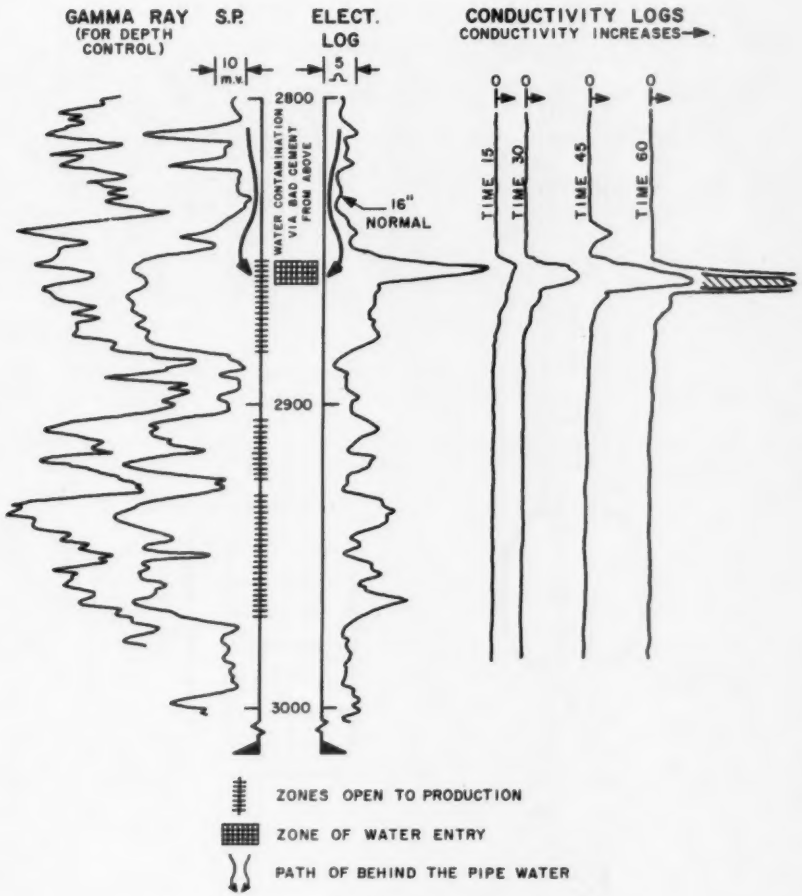


FIG. 18. Water entry (cased borehole) by conductivity logs.

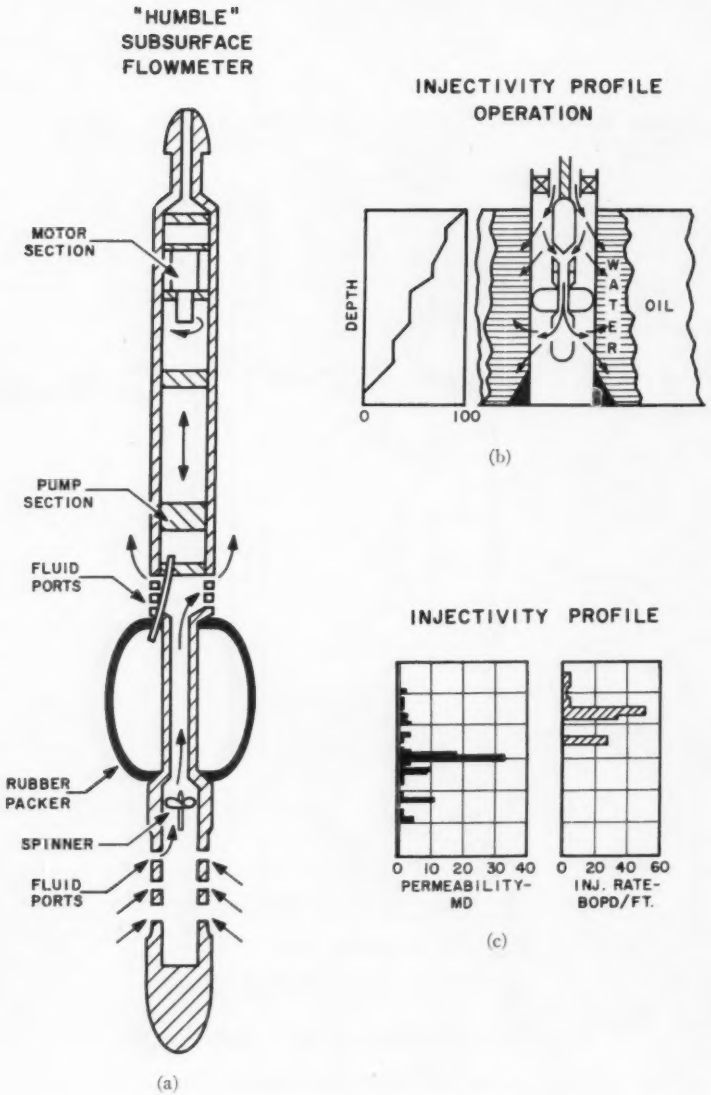


FIG. 19. Flowmeter and Injectivity Profile

logging devices, has made the oil industry more aware of the nature of production well logging. More efficient means of well production and greater recoveries will be achieved by research and development in the field of production well logging.

REFERENCES

Bailey, B. H., Bryant, H. L., and Powell, N. L., 1957, Spot those gas zones with neutron logging: Oil and Gas Journal, n. 46.

Caldwell, R. L., and Sippel, R. F., 1958. New developments in radioactive well logging research: Bull. Amer. Assoc. Petr. Geol., v. 42, n. 1.

Dewan, J. T., and Allaud, L. A., 1953, Experimental basis for neutron logging interpretation: Petr. Engineer, v. 25, n. 9.

Grosmangin, M., and Walker, E., 1957, Gas detection by dual-spacing neutron logs in the Greater Oficina area, Venezuela: Jour. Petr. Tech., v. 9, n. 5.

Hawthorne, M. M., Private communication: REMCO, Fort Worth, Texas.

Introduction to Schlumberger well logging: 1958, Schlumberger, Document 8.

Mott, W. E., and Ediger, N. M., 1959, Nuclear well logging in petroleum exploration and production: Fifth World Petroleum Congress.

Rumble, R. C., Buck, H. M., and Peters, B. A., 1959, New subsurface flowmeter: Oil and Gas Journal, v. 57, n. 20.

Swift, G., 1952, Simultaneous gamma ray and neutron logging: Geophysics, v. 17, n. 2, p. 387.

Wyllie, M. R. J., 1957, The fundamentals of electric log interpretation: Second edition, Academic Press, Inc., New York.

Youmans, A. H., and Zimmerman, C. W., 1959, Recent advances in the use of nuclear physics in oil well surveys: Fifth World Petroleum Congress.

GEOPHYSICS, VOL. XXV, NO. 4 (AUGUST, 1960), PP. 928–938, 7 FIGS.

ELECTRICAL ANALOG APPROACH TO DIPMETER COMPUTATION*

T. H. BRAUN† AND G. Y. WHEATLEY‡

ABSTRACT

An electrical analog instrument has been developed to calculate dip and strike from continuous dipmeter logs. The particular model described is designed specifically for the Schlumberger CDM-P, or Poteclinometer, logs and it can be used with hole deviations of up to 36 degrees.

Every control on this instrument corresponds to one of the recorded parameters of the dipmeter log. It is thus easy to see the effect of any one parameter on the resolved dip and strike. The instrument is portable and can therefore be used at the well site, if necessary, to make on-the-spot decisions regarding further drilling operation after a dipmeter log has been run. No elaborate training in procedure is required.

The rapidity with which the computations can be made also permits a larger number of levels to be computed. This frequently results in more accurate information and a considerable saving in computation expense.

INTRODUCTION

An electrical network analog, or analog computer, that was developed to compute the dip and strike from a continuous dip-meter log is described. The importance of the continuous dipmeter as a structural tool is recognized by all petroleum geologists. Whereas all other logs define a point in space, the dipmeter log transforms this point into a vector, both of direction and magnitude. Yet the full potential of this tool is seldom realized because of the lack of a completely satisfactory way of computing the data.

The advantages of the analog computer which has been developed to meet this requirement are: (1) sufficient accuracy for most geological work, (2) it requires no multiplicity of charts, (3) computation can be made in a simple and rapid manner, and (4) it is compact and easily portable to the well site if desired. It should be noted, however, that the accuracy of computations using this or any other computer is limited by those errors inherent in the dipmeter survey itself, particularly in intervals of poor or questionable correlation where errors in the basic data may be large.

By way of introduction to the analog computer, a brief review of the dipmeter is in order.

CONTINUOUS DIPMETER

The continuous dipmeter is a survey instrument run in a hole for the purpose of determining the amount and direction of dip of the formations traversed by the borehole. Three electrodes, spaced 120° apart, register the formation changes encountered. Correlation of the three curves establishes the amount of displace-

* Presented at the joint meeting of the Pacific Coast Sections AAPG-SEG-SEPM, Los Angeles, November 7, 1958.

† System Development Corporation.

‡ The Superior Oil Company.

ment. The hole diameter is recorded by a caliper log, run simultaneously with the continuous dipmeter. The above four curves are recorded on the right side of the continuous dipmeter logs.

On the left side of the log three so-called orientation curves are recorded. Since the tool is free to rotate, the orientation of the No. 1 electrode is recorded with respect to magnetic north. And, since the boreholes are seldom vertical, the inclination of the hole must be recorded. In the CDM-P, or Poteclinometer log, one curve records the azimuth of the hole inclination with reference to electrode no. 1 (Relative Bearing); the second curve records the angle of inclination directly.

These seven curves are the variables in the dipmeter problem and any solution must involve all seven parameters.

The electrical analog instrument developed to perform these computations is illustrated in Figure 1. This particular model is arranged to work with the logs obtained with the most recent of the Schlumberger dipmeter tools, the CDM-P, or "Poteclinometer," tool. Another version is available to solve the CDM-T, or "Teleclinometer" logs. The basic difference between these instruments, as with the logs, is in the method of handling the hole deviation data. Although there are also differences in the electrode configurations, these are immaterial to this discussion.

On this analog computer, each of the controls, with one exception, corresponds to one of the recorded parameters of the dipmeter log, and in most cases, the operation consists merely of setting these controls to agree with the recorded log parameters and reading the resolved dip and strike. The actual procedure will be discussed in more detail later. In front of the instrument is a data sheet to which the basic data from the log is transferred. To facilitate extracting the data from the log, a transparent overlay template was developed. This merely duplicates the scale calibrations on the heading of the log and makes it easier to measure the log parameters at any desired depth. This template may be seen on top of the dipmeter log, to the right of the data sheet. An entire level computation can be easily carried out in less than two minutes and more than one hundred levels can be computed in a normal working day.

Figure 2 is similar to many illustrations that have been used to illustrate the principles of dipmeter logging. In that it serves as a good introduction to analog methods, however, it may be used as a starting point for a simplified description of the electrical circuitry on which this instrument is based.

The reference plane is a plane normal to the axis of the borehole which contains the three measuring electrodes or caliper arms at any one time. Above this reference plane is drawn a formation plane. For the purpose of this illustration, these planes are not parallel. As a result, when the three electrodes pass through the formation plane during the logging operation, the three recorded curves of the sensing electrodes will show the displacements shown on the right of the slide. These displacements, measured from the reference plane, are called E_1, E_2,

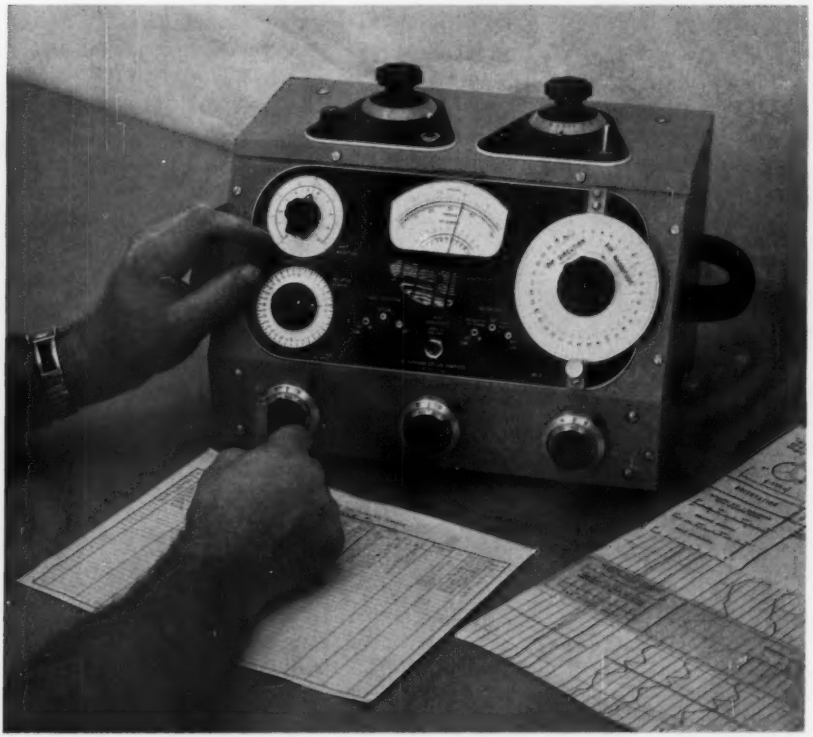


FIG. 1. Electrical analog computer in use.

and E_3. The *difference* between these displacements is a measure of the attitude of the formation plane with respect to the reference plane. In dipmeter parlance, the maximum angular difference between these planes is the *uncorrected dip*, so-called because the deviation of the borehole has not been taken into account.

Imagine, for the moment, a plane of electrical potential which is raised above a ground, or reference, plane by means of voltages E_1, E_2, and E_3. If this were in reality a plane, one could imagine equipotential lines corresponding to contour lines along the strike of the plane, and the maximum voltage gradient would exist at right angles to these lines, corresponding to the direction of maximum dip.

We can start by making this plane of an electrical resistance material. If the three voltages now are connected to three points located on a circle within this plane, current flows and voltage drops will be established.

Figure 3 illustrates such a plane with all of the material removed from it except for a ring of the resistance material just mentioned, and the electrode voltages are connected to three points spaced equidistantly about the ring.

Voltage E_1 is greater than E_2 or E_3, and E_2 is equal to E_3. Therefore a line drawn through E_2 and E_3 is an equipotential line in our imaginary plane, or a strike line in our geological analogy. The same applies to any line drawn parallel to this line. The greatest voltage difference, measured diametrically across the ring, will be found at right angles to these lines. This is better illustrated in Figure 4, which shows two views of our resistance ring, or circular potentiometer.

In this illustration a pair of contacts (the arrow heads) has been added which are spaced 180° apart and which can be rotated around the potentiometer ring. To these rotating contacts is connected an electrical meter that indicates the voltage difference which exists at opposite points of the circular potentiometer.

With the voltages depicted, the voltage gradient will be as shown, and, with the contacts as shown in (A), the meter will indicate a maximum value. With the contacts rotated as in (B), no voltage difference exists at the opposite sides of the potentiometer ring and the meter indicates zero. In other words, the contacts are now arranged "on strike."

Just as any three points not in a straight line determine a plane, so do any

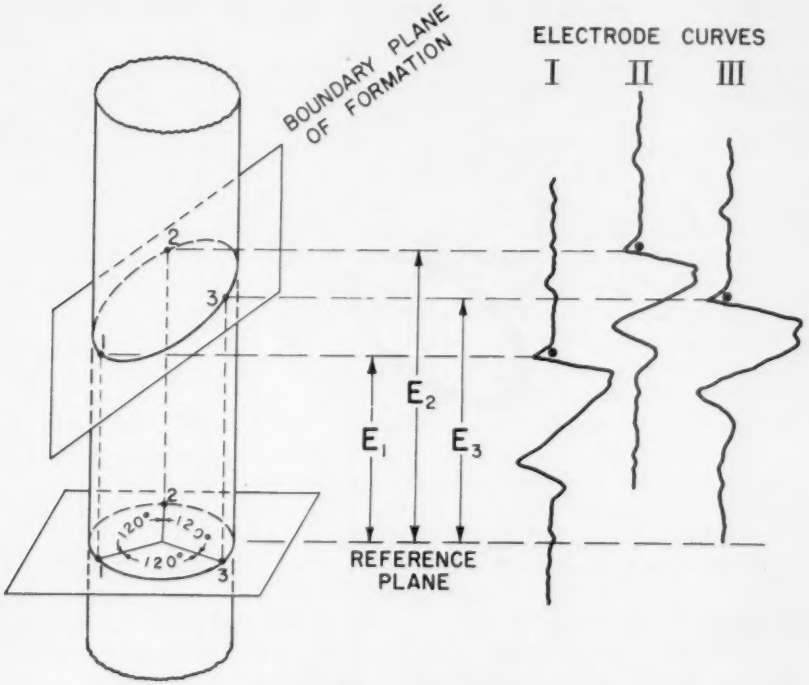


FIG. 2. Schematic drawing showing the generation of dipmeter curves.

three voltages in this network yield an equivalent "electrical plane" whose slope can be determined by the measure of the voltage difference across the network and whose strike can be determined by the direction of zero voltage difference.

Therefore, if the electrode voltages are made to correspond to the elevation differences of the dipmeter curves as measured from a reference plane, the indicating meter can be calibrated in terms of dip magnitude. The scale calibrations will not be linear increments but will vary as the tangent value of the angle.

The position of the contact arm assembly of the potentiometer is read against a 0–360° circular scale. From this scale the strike direction is obtained at the null point. If this 360° scale is made moveable, it can be used to correct for the orientation of electrode no. 1.

In actual practice the strike direction is not wanted so much as the direction of maximum dip. However, because the null method is the most accurate direction indicator, both from electrical and geometrical considerations, the null method is used to obtain the strike direction but the pointer is displaced 90° and thus the direction of dip may be read. This is illustrated by the open arrow in (B) of Figure 4.

Still unaccounted for is a method by which the effects of hole size and hole

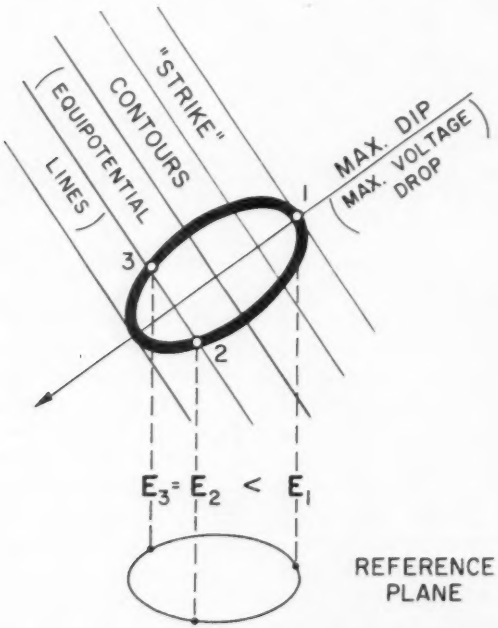


FIG. 3. Schematic drawing showing the analogy between strike contours and equipotential lines.

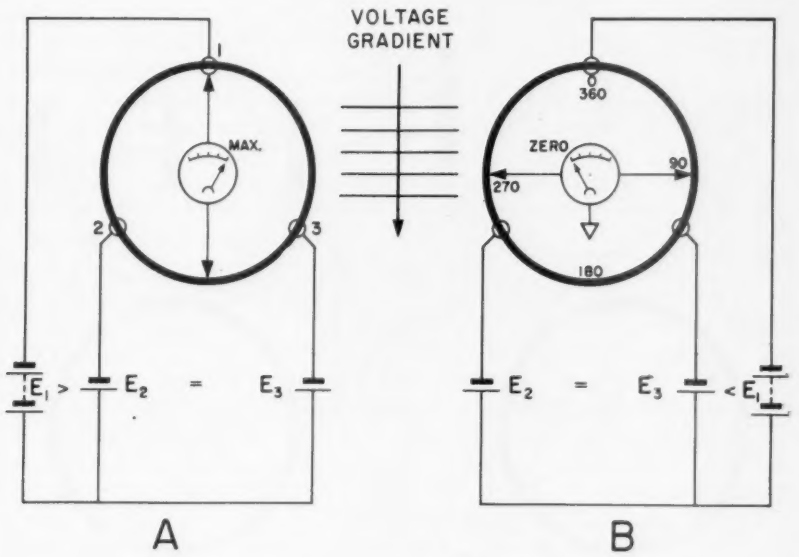


FIG. 4. Two illustrations of the basic resolver circuit.

deviation can be accounted for. The circuitry by which this is accomplished is shown in Figure 5.

Here is the basic electrical circuit of the analog computer. On the right is the same circular potentiometer that was shown in Figure 4. The three taps at 120° intervals are connected to three variable voltage controls. These controls correspond to the dipmeter electrode curves. Note that the voltage which supplies all three of these controls is adjustable by means of a fourth voltage control. This changes the *magnitude* of the dip voltage indicated on the meter but maintains the same *ratio* of voltages to the three taps. The direction, therefore, is not affected. This, then, corresponds to the hole diameter parameter, for as the hole diameter varies on a dipmeter log, only the magnitude of the uncorrected dip will change, but not its direction.

The hole deviation voltage is applied to our resolver potentiometer by another similar potentiometer, located on the left of the figure. The two contact arms of this potentiometer go to a variable voltage which is calibrated in terms of hole deviation magnitude. The position of this voltage on the potentiometer ring can be rotated through the full 360° to agree with the drift direction. These controls, then, simulate the hole deviation direction and magnitude electrically. By connecting the three taps of the hole deviation potentiometer to the three taps of the uncorrected dip, or resolver, potentiometer, all the voltages can be resolved in terms of formation dip magnitude and direction.

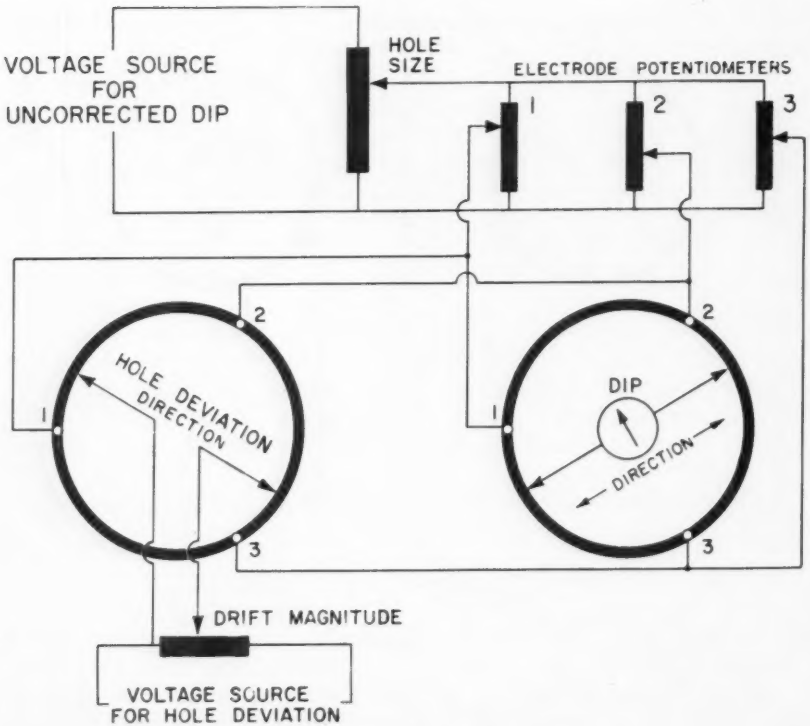


FIG. 5. Fundamental electrical circuit of the analog computer.

Figure 6 is a close-up of the instrument shown in Figure 1, and in this photograph the actual arrangement of the controls mentioned above can be seen. As mentioned previously, there is one control that does not correspond to any of the log parameters and this is the line voltage control. This control, which corrects for the variations that exist in the a.c. line voltage, is the left hand control on the top surface.

To its right is the hole diameter control—it is calibrated to cover a range of 6 inches to 20 inches in hole diameter.

On the bottom of the front panel, the vertical section, are three identical controls. These are the three electrode voltage controls, and they are calibrated in inches, from 0 to 10 inches. In other words, a maximum range of 10 inches in the relative displacement of the three electrode curves can be accommodated.

The remainder of the controls are on the sloping panel. To the left are two circular dials, one above the other, which have to do with hole deviation. The lower dial is calibrated from 0 to 360° and it corresponds to the "relative bearing" trace of the Schlumberger dipmeter log; the upper dial is calibrated in

terms of drift magnitude. There are two scales on this dial, one from 0 to 10°, the other from 0 to 36°. The scale selection is made by a switch to the right of the "relative bearing" dial.

The electrical meter in the center of the panel indicates the *magnitude* of the formation dip. On the right side is the large circular dial assembly from which the dip *direction* is obtained.

The meter has two sets of scales; the upper ones from 0 to 50°; the lower ones from 0 to 10°. The choice of scale sensitivity is again made by a switch, this time by the one to the right of, and slightly below, the meter.

Although it may not be apparent from the figure, there are actually two dials involved in the right hand dial assembly. The lower, or underneath, disk is a white compass card graduated from 0 to 360°, and it is free to rotate. This card is rotated to agree with the orientation of the no. 1 electrode and is then clamped by the knurled thumb screw on the bottom of the dial assembly.

The upper, or outer, disk is made of clear lucite and this disk is connected to the resolver potentiometer. This lucite dial has on it the fiducial mark from which the dip direction is read off against the white dial underneath. This fiducial mark incorporates the correction for magnetic declination and thus eliminates the confusion as to whether the declination should be added to or subtracted from magnetic north, or rotated to the left or the right on the stereonet.

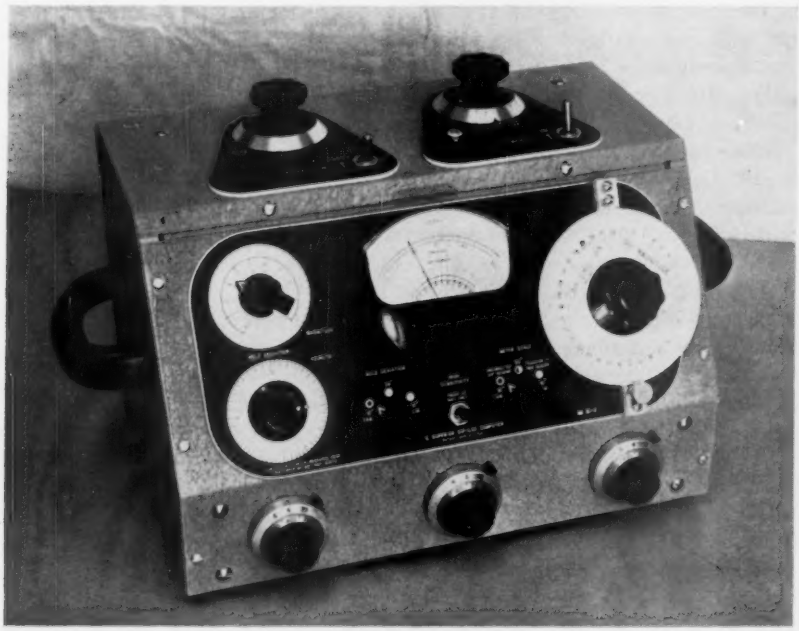


FIG. 6. Close-up view of the instrument.

Briefly, then, to obtain the resolved dip and strike, the data is transferred from the dipmeter log to the data sheet. The line voltage calibration is checked, the meter scale switch set on the 50° position, and the hole diameter and hole deviation controls set to agree with their recorded log counterparts. The three electrode potentiometers are then set to agree with the observed displacements of the recorded electrode curves. The white azimuth dial is rotated to agree with the orientation of the no. 1 electrode and clamped in place. The dip and strike reading may now be obtained.

To do this the lucite dial is rotated until a maximum reading is obtained on the meter scale. If the maximum is less than 10° on the scale, the meter selector switch is thrown from the 50° to the 10° position. This maximum meter reading, in degrees, is the dip *magnitude* and is so recorded on the data sheet.

The lucite dial is now rotated in a clockwise direction until the meter pointer reads zero. At this point, the *direction* of dip is read from the white azimuth dial under the appropriate fiducial mark of the lucite dial.

The whole sequence takes just about as long as it takes to describe it. Under some cases, with high hole deviations or dips greater than 50°, an extra step may be necessary.

There were several reasons for the limit of 50° on the maximum scale calibration. For one thing, a 10-inch electrode displacement was convenient because of the commercial availability of pre-calibrated dials for the precision potentiometers; a 10-inch maximum displacement is equivalent to a 50° dip for a hole diameter somewhere between 11 inches and 12 inches. If the meter scale were calibrated for greater than 50° of dip, the necessary tangent law calibration would also result in excessive crowding of scales for the values below 50°.

However, even though the majority of dips that are worked are less than 50° magnitude, it was felt desirable to be able to work dips of greater than 50°. This is done by the use of one supplemental chart. See Figure 7. The technique calls for dividing the three electrode displacements by ten and entering these values into the machine. An uncorrected dip value will now be obtained that is smaller than the value of the true reading. From Figure 7 we can find the true value of uncorrected dip in terms of this smaller, reduced, reading. Obviously, by this means values of dip magnitude can be obtained that correspond to electrode displacements of 100 inches instead of 10 inches, or dip values in excess of 80°. The hole deviation magnitude is also reduced by a factor of ten and a linear set of meter calibration used to obtain the resolved dip. Thus, dips of greater than 50° can be worked with the use of but one supplemental chart and at slightly reduced accuracy. The amount of hole deviation that can be handled, however, is still limited to 30°–35°, for above this value of hole deviation the use of a plane trigonometry approach, as exemplified by this computer, results in azimuth errors of over 5° and a spherical trigonometry solution must be applied.

Experience and tests with this instrument indicates that when using the 50° scale the maximum error of dip *magnitude* due to the computer itself will not be over 1° to 1½° plus 5 percent of either the uncorrected dip, resolved dip, or hole

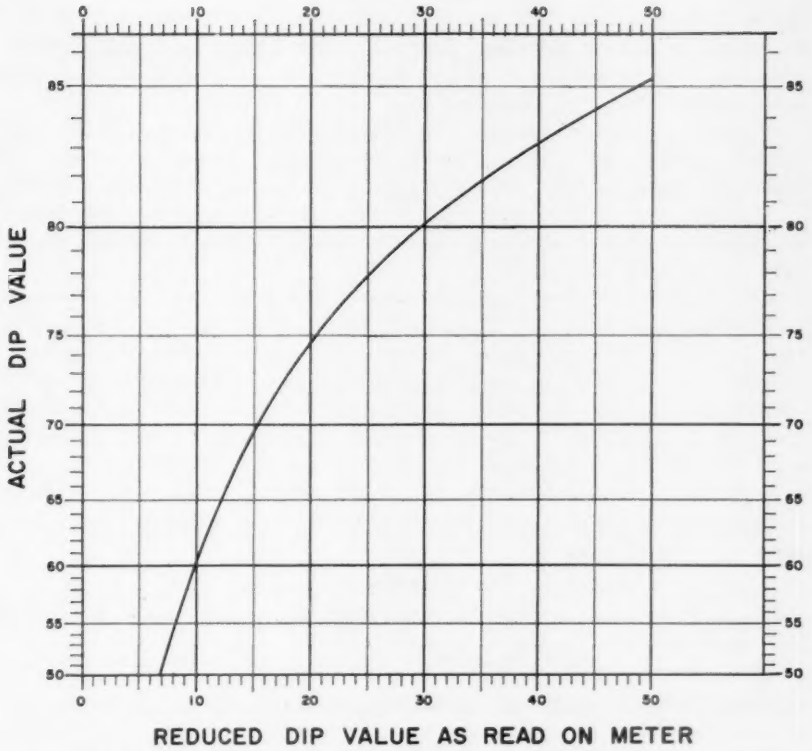


FIG. 7. Conversion chart used to obtain formation dips of more than 50° when electrode curve displacements have been divided by 10.

deviation, whichever is the higher. Generally the higher the hole deviation, the higher the error, within the limits mentioned. On the 10° scale, the maximum error is somewhat less.

The other error that concerns us is the error in dip *direction*. Due to the null current method of determining the dip direction, the error here is not over 5°, provided that the hole deviation is not over 30°. Here again the error is to a considerable degree a function of hole deviation magnitude. As a matter of fact, the only time the directional error exceeds 5° is when both the hole deviation and uncorrected dip are of the same order of magnitude and in the range of 30° to 35°. As the uncorrected dip gets steeper than 35°, and because the hole deviation range is limited to 35°, the error again becomes smaller.

Fortunately, the maximum values for the two errors never coincide. The maximum error of dip magnitude occurs when the hole deviation and the uncorrected dip are in the same plane; i.e., when the dip magnitudes can be added or

subtracted algebraically. In this plane, the dip direction error is small. Generally, the maximum value of directional error will be found when the direction of hole deviation and direction of uncorrected dip are (roughly) at right angles. In this condition, the error of dip magnitude tends to be very small.

The above accuracy compares with Brunton compass accuracy and it is considered more than adequate when taking into account the over-all accuracy of dipmeter logging methods and the variations present in the geological model.

Because there are no vacuum tubes or other fragile components used, or batteries that can deteriorate, the ruggedness and reliability of this instrument have been proved to be very good.

In summary, an electric analog computer has been developed for dip computations which is fast and easy to use. Its simplicity of operation allows anyone on the geological staff to compute his own dipmeter logs, and also to see instantly the effect of variation of any one parameter which may be in doubt. It is portable enough to be taken to the well site and thus help make decisions that may save many hours of rig time. It has enough accuracy and range for most geological work. Computation is sufficiently rapid that it is entirely practicable to calculate a large number of levels wherever geologically desirable, either on new wells or those already in the files, an approach which is certain to extract more data from each dipmeter log.

REFERENCES

Boucher, F. G., Hildebrandt, A. B., and Hagen, H. B., 1950, New dip-logging method: Bull. AAPG, v. 34, p. 2007–2026.

Claudet, A. P., 1950, Geological interpretation of dipmeter results: A.P.I. Drilling and Production Practice, N. Y., p. 168–177.

Continuous physical dip logging: Laboratory bulletin, Halliburton Oil Well Cementing Co., Duncan, Oklahoma.

de Chambrier, P., 1953, The microlog continuous dipmeter: Geophysics, v. 18, p. 929–951.

De Witte, A. J., 1956, A graphic method of dipmeter interpretation using the stereo-net: Pet. Trans. AIME, v. 207, p. 192–199.

Doll, H. G., 1943, The S.P. dipmeter: Pet. Tech., v. 6, Tech. Paper 1547.

Ferre, M., and Kinnaird, R., 1957, Dipmeter curve comparator, an optical aid to the interpretation of dipmeter data: Rev., Sci. Instr., v. 28, p. 690–693.

Franks, C., and White, W., 1957, More from your dip-log surveys: Oil and Gas Jour., April 8, p. 102–105.

Grynberg, J., and Ettinger, M. I., 1957, The continuous dipmeter: Oil and Gas Jour., Part I, April 1, p. 166–178, Part II, April 22, p. 129–139.

Introduction to Schlumberger well logging: Schlumberger Document n. 8, p. 141–155.

McClellan, H., 1948, Core orientation by graphical and mathematical methods: Bull. AAPG, v. 32, p. 262–282.

Prescott, B. O., 1955, Graphical method for calculating dip and strike from continuous dipmeters: Oil and Gas Jour., March 7, p. 118–125.

Sasseen, J. H., 1957, An electronic analog cross correlator for dip log: I.R.E. Trans on Electronic Computers, Sept., p. 182–187.

Stratton, E. F., and Hamilton, R. G., 1947, Application of dipmeter surveys: AIME meeting, Tulsa, Oct. 8–10.

Swift, G., 1959, Dip-log computer chart: Jour. Pet. Tech., v. 11, p. 23–28.

GEOPHYSICS, VOL. XXV, NO. 4 (AUGUST, 1960), PP. 939-947, 8 FIGS.

COLLECTION AND PROCESSING OF DIGITIZED ACOUSTIC LOG DATA*

R. A. BRODING† AND J. L. POOLE‡

ABSTRACT

The mathematical processes involved in making acoustic logs useful for the geophysicist or production analyst have prompted the handling of log data by digital means. Digital punched tape logs from retraced analog recordings as well as digital recordings made by punching tapes directly from the recording galvanometer signal obtained during a logging survey are being used as input to electronic computers. These computers can be programmed to perform the normal computations now used in data reduction. This process yields higher precision data and allows computational procedures to be performed that previously were considered burdensome or tedious. The technique is attractive in preparation of geophysical logs, synthetic seismograms, calculating effective porosities and saturations. However, the requirement of converting recorded digital data to be compatible with the input of different digital computers and to all the various formats for individual programs is a problem that will require standardization in formats. It is evident that the advantages to be realized in data reduction processes will require the log of the future to be recorded in digital as well as analog form.

INTRODUCTION

Most known logging techniques require that some form of computational procedure be used if we are to realize the full value of the logging method. The acoustic log is no exception, and it is apparent that more detailed computational methods will be employed if the full worth of this log is obtained. Analog computer methods have been applied to the acoustic log and have materially aided in reduction of the data. Such devices as curve linearizers, ball and disc integrators and scale converters are in this category. There is a problem in the degree of accuracy of these devices as well as restrictions on the range in which they can work. It can be said that the inherent accuracy in such systems leaves much to be desired.

During recent years research laboratories have applied their digital computers to computations on well logs. The applications were generally in problems that required detailed computational procedures to be used. It was felt that the interrelation of data from various logging methods contained useful data which were beyond that being used in normal visual correlations and simple calculations. A major barrier existed in this approach as the normal recording of logs in the analog form required tedious work to convert these logs to digital form.

This conversion problem has been attacked in numerous ways including measuring values directly from the log by a rule, and hand-tabulating; to elaborate machines that allow indexing of pointers to the log and will, on command,

* Presented at 13th Annual Midwestern Exploration Meeting, Shreveport, Louisiana, April 4, 1960. Manuscript received by the Editor March 15, 1960.

† Century Geophysical Corporation.

‡ Century Geophysical Corporation of Canada.

translate the position of these pointers into scaled values or directly to an IBM punch card.

INSTRUMENTATION

In considering this problem a hand-following type curve tracer was devised wherein an analog recorded log could be traced to produce a paper punch tape. Similarly the digitizing equipment could be operated directly from the output of a sonic logging truck system. The basic system of these two methods is shown in Figure 1.

In field digitizing, the sonic log signal to the camera recording galvanometer was also connected to the input of a digital voltmeter. The output of the voltmeter drives a paper punch via punch drive amplifier and control. The command to punch is derived from a photocell light shutter connected to the logging truck camera film drive so for each ft of depth a reading is made. Thus a digital punch entry is made on the paper tape for each ft of hole depth. A truck-mounted installation is shown in Figure 2.

In the case of the curve tracer input the mechanical linkage of the tracing board is connected to a linear potentiometer that allows a voltage proportional to trace amplitude to be obtained. This voltage is properly scaled in a normalizer panel then treated similar to the field log system by the digital voltmeter. However, a different problem exists in deriving the punch command. The requirement is for having one punch entry per ft of depth independent of total depth with an error not to exceed one entry or one ft. This requirement was satisfied by a novel means. A photocell pickup gave a pulse rate proportional to the chart drive speed by counting a sector wheel on the drive motor shaft. By using a preset counter these pulses were counted to a number equivalent to one ft of hole

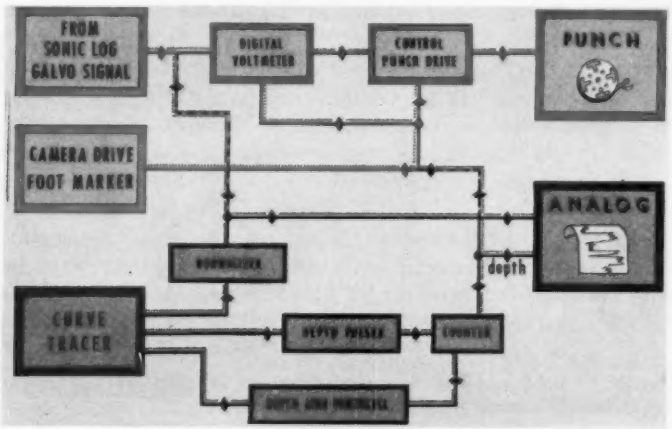


FIG. 1. Basic steps in digitizing field and office log data.

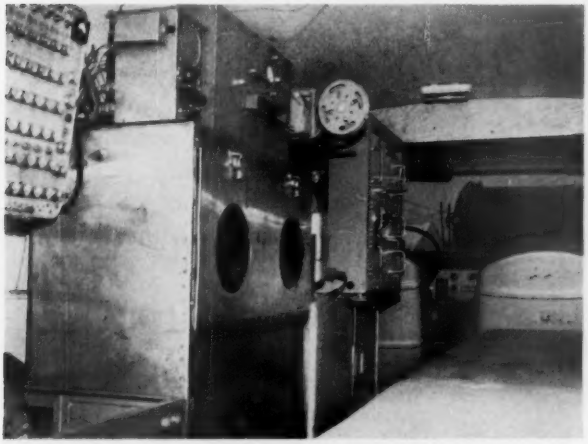


FIG. 2. Truck installation of digital recording equipment.

depth on the chart drive. To overcome paper stretch a second photocell pickup sensed the depth lines on the log. The output of this photocell overcontrolled the present counter to force it to start counting on each depth line. Therefore, the system was resynchronized on each depth line and is unable to be in error by more than one ft independent of log length or number of depth lines. Provisions were included for also re-recording the analog retraced log for scale conversions. A complete tracing scheme is shown in Figure 3.

A binary coded decimal form was used on the paper tape with four digits being punched for each reading. The range of values covered 040.0 to 199.9 microseconds per ft. The density of measurements was standardized on the basis of one reading per ft of depth. Since readings are sequential there is no need for carrying a depth count. The depth is simply the number of entries added to the depth of the first reading. The tape format is illustrated in Figure 4.

DATA PROCESSING

A simplified schematic of the data processing procedure is shown in Figure 5. In reduction of sonic log data for the geophysicist a program was set up wherein seismic check shot times were stored in the computer along with the check shot levels. The log punch tape is then read into the computer and comparisons made against the check shot times by making a running integration to each shot level. If an error existed, the error was evenly distributed over the interval between check shots and a reintegration made to force fit the data to the check shot times. A more elaborate program could be made to allow corrections to be graded over localized log sections as selected by an interpreter. However, this has not been done to date.

FIG. 3. Office curve follower and digitizer.

The average velocity and interval velocity were also machine calculated and a tabular print-out of this data was made on a 10-ft of hole depth basis as well as each tie point level. This gives approximately one millisecond time interval between data points and is considered adequate density for geophysical use. The format of the tabular output is shown in Figure 6. Thus a complete geophysical survey was made that was essentially "untouched by human hands" except for picking of check shot times.

Once the data is in the digital form and corrected, it can be easily machine computed for other uses. For example, a synthetic record was made by assuming a reflection coefficient changes in proportion to the log of velocity, as previously suggested by Peterson (1955). The one-way travel time on a $\frac{1}{4}$ millisecond interval was machine computed along with the log of velocity and tabulated.

These data were processed by United Geophysical who recorded the computed information on magnetic tape and played the tape back in real time through simulated ground filters and appropriate seismic filters to produce a "primary" synthetic record (Figure 7). If it is desirable to study multiples, they may be

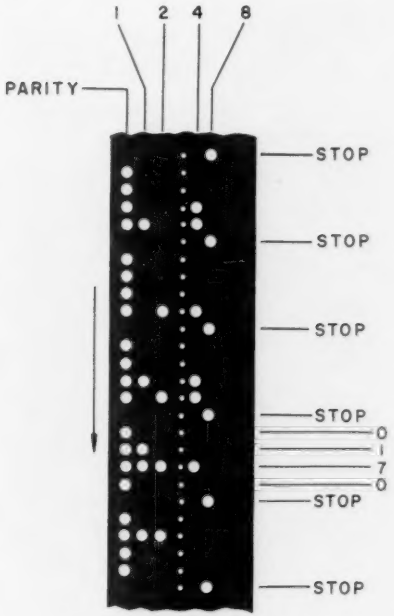


FIG. 4. Punch tape format. Binary coded decimal punch tape.

introduced during the machine computing process. The digital procedure has advantages over the analog for production of synthetics because it is not limited to any one method of computing the reflection coefficients, transmission coefficients, multiples, etc. It also lends itself to studies of thinning and thickening sediments since sections of the log can be cut out or added.

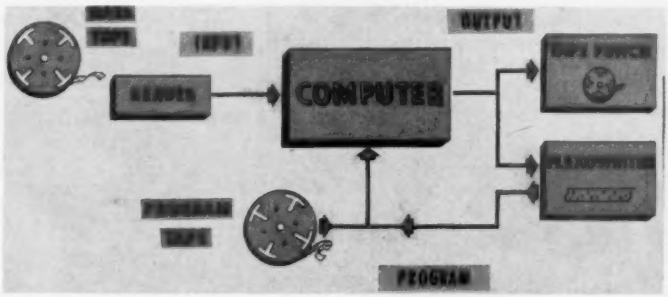


FIG. 5. Basic Data Processing Equipment.

DEPTH (Dgm)	UNCORRECTED INTEGRATION	CORRECTED INTEGRATION	AVERAGE VELOCITY	INTERVAL VELOCITY
4890	.4439	.4434	10782	16926
4900	.4445	.4439	10792	16638
4910	.4451	.4445	10801	18726
4920	.4457	.4450	10812	17482
4930	.4462	.4454	10823	17241
4940	.4468	.4459	10833	17511
4950	.4475	.4465	10843	17458
4960	.4479	.4470	10853	17667
4970	.4485	.4475	10863	16128
4980	.4491	.4480	10872	17241
4990	.4496	.4485	10882	16778
5000	.4502	.4491	10891	16778
5010	.4509	.4496	10900	16778
5020	.4514	.4501	10910	16666
5030	.4520	.4507	10919	16863
5040	.4527	.4512	10928	18115
5050	.4532	.4517	10938	17905
5060	.4538	.4522	10948	17857
5070	.4544	.4528	10957	16863
5080	.4550	.4533	10866	17241
5090	.4556	.4538	10975	17094
5100	.4561	.4543	10985	17361
5110	.4567	.4548	10994	16750
5120	.4573	.4554	11003	17153
5128	.4579	.4559	11008	14008
5130	.4586	.4560	11010	14706
5140	.4586	.4566	11017	17361
5150	.4593	.4573	11023	15600
5160	.4600	.4580	11028	13404
5170	.4607	.4587	11032	13586
5180	.4615	.4595	11034	14513
5187	.4620	.4600	11031	14914

FIG. 6. Format for data from computer.

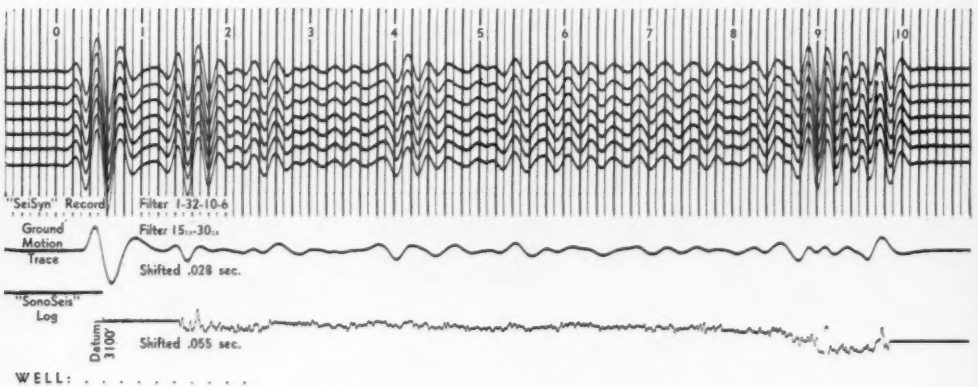


FIG. 7. "SeiSyn" synthetic from computer digital data.

FUTURE LOG COMPUTER APPLICATIONS

Today the log analyst has a number of established relationships between the various well logged parameters and parameters necessary to evaluate a reservoir or help the geophysicist in his search for new reservoirs. Some of these relationships are shown in Figure 8 along with source or log data and the desired results. In some cases a desired result can be obtained from a single log while in other types of logs several are required. The following examples illustrate such procedures.

Wyllie, Gregory and Gardner (1956) first proposed the Time Average formula as a means for deriving porosity from the velocity measurement:

$$\frac{1}{V \log} = \frac{\phi}{V \text{ Liquid}} + \frac{1-\phi}{V \text{ Matrix}}.$$

This relation of porosity to velocity has been widely used with remarkable success. It has been important in production evaluations and easy to apply as porosity values can be obtained directly from the velocity log. To obtain a measure of net ft of porosity pay, the integral of travel time over the production zone times the conversion factor gives total porosity ft directly. This computation is easily obtained from the digital log.

More recently electric logs have been used complementary with the velocity log to determine percent water saturations.

Water saturation is normally determined from the formation factor and the ratio of formation water resistivity to the true resistivity of the rock. Since the

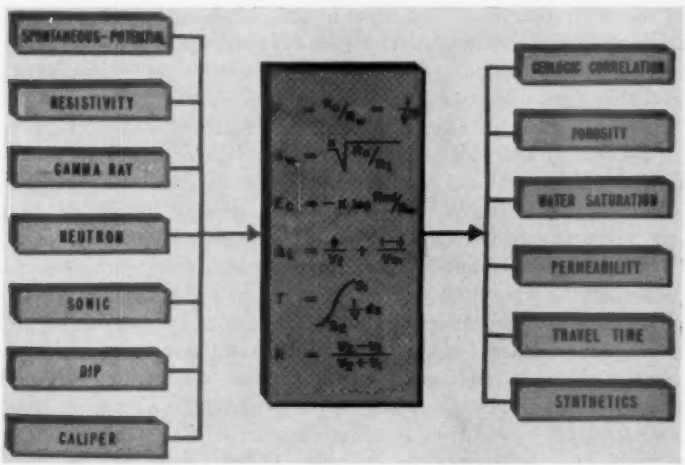


FIG. 8. Common computations, log types and desired results now being performed by log analysts.

formation factor is equal to the reciprocal of the porosity squared, its value is then obtained from the sonic log. The value of true resistivity is an electric log measurement and, in some cases, can be obtained directly from the highly focused induction logs. The water resistivity is obtained from direct measurements of water samples or derived from the SP curve. Therefore, all the required data can be obtained from an electric and sonic log. If digitized electric and acoustic logs were available, this solution also could be made on a computer. This example is given only to illustrate one type of computation where the interrelation of two types of logs is used to obtain the desired measurement. In practice some of these interrelations may be best solved by present computational procedures, but the advantage of a digital process will merit its use in examples where repetitive and tedious computations are required.

In its original concept the acoustic velocity log was devised primarily as a means of obtaining detailed velocity information to aid the geophysicist in picking reflection horizons and to determine the velocity to these horizons for interpretation of surface seismograms. However, it was believed that an acoustic measurement was more informative than electrical measurements of the physical properties of rock. Therefore, it was expected that more useful data other than velocity could be obtained. The question then is, what can we expect to determine further from this log?

The Time Average formula contains a term dependent upon fluid velocity. It is natural to speculate on using this term to give a means for identifying fluid types. The work of Hicks and Berry (1956) on the "Application of Continuous Velocity Logs to the Determination of Fluid Saturation of Reservoir Rocks" showed that the velocity decreased with porosity and with increased compressibility of the saturating fluid. The effect of the compressibility of the saturating fluid was most easily observed in high porosity formations, i.e., greater than 20 percent porosity. This characteristic would seem to be highly important in some areas and, therefore, undoubtedly will be exploited further.

In lithologic studies the acoustic log has proved to be excellent. It is expected that this application will be expanded, particularly as more logs are available.

Since the elastic constants of the grains comprising the rock framework, the type of cementing material on these grains, grain density, density of the fluid in the pores, pressure on the rock skeleton, pressure on the fluids, porosity, compressibility of the fluids, and temperature enter into determining the rock velocity, there may be a possibility of determining each of these effects separately. Each of these measurements implies additional information must be measured and, by proper application of established relationships, a computed or derived measurement may be possible to separate the effects. To explore, test, and verify such measurements requires tedious handling of large volumes of data. This barrier is minimized by resorting to automatic computing machines.

The problem is not simply the collecting of the prime data in digital form because, once this step is accomplished, we find there are nearly as many formats

for the information as there are computers that could use the data. The different forms of digital recording are basically punch cards, punch tape, and magnetic tape. Most computers now being used require punch cards as these computers were designed primarily for accounting work where cards are well suited. In setting up the program for a computer the card format may have a number of different forms. Therefore, these machines require not only card input but also the information on the card punched to fit the program.

Punch tape can be in a number of different codes and levels. A similar situation exists with magnetic tape. Therefore, another problem exists in transforming the digitized tape into a usable form for tape input to computers other than that which matches the field tape. It appears that the only solution is another computer to receive the punch tape and to translate this information to cards or tape of the required format. This unnecessary complication can be remedied only by standardizing on the input format for computers.

CONCLUSION

It is evident that the log of the future will be recorded in digital form as well as in analog form. The requirement for on-the-spot analysis of logs at the well site necessitates the retaining of analog presentation. The step of digital recording will be a major one to free technical manpower for deriving more useful data from logs and one in which the digital computer will play a leading role.

REFERENCES

Hicks, Warren G., and Berry, James E., 1956, Application of continuous velocity logs to determination of fluid saturation of reservoir rocks: Geophysics, v. 21, p. 739–754.

Peterson, R. A., Fillippone, W. R., and Coker, F. B., 1955, The synthesis of seismograms from well log data: Geophysics, v. 21, p. 516–538.

Wyllie, M. R. J., Gregory, A. R., and Gardner, L. W., 1956, Elastic wave velocities in heterogeneous and porous media: Geophysics v. 21, p. 41–70.

DEPARTMENTS

DISCUSSIONS AND COMMUNICATIONS

DISCUSSION ON "PHOTOMECHANICAL METHOD OF FREQUENCY ANALYSIS OF SEISMIC PULSES"*

ROBERT C. MOODY†

I would like to add an observation to the paper, "Photomechanical Method of Frequency Analysis of Seismic Pulses," GEOPHYSICS, v 24, n. 4, by B. F. Howell, et al.

The method described in Howell's paper has been employed by others, including the Techno Instrument Company. Our method has been refined to provide automatic graphing, a high resolution and an extended frequency range. We go about this in the following manner.

By means of a gate, which is both amplitude sensitive and of fixed delay, we capture the transient on a magnetic drum. The transient may now be made periodic by revolving the drum. It is surveyed on a cathode ray oscilloscope, and by means of a muting circuit, all of the extraneous and non-relevant noise preceeding and following the transient is blocked out. Thus we have the transient alone.

A Fourier series is produced from the "periodic transient." By proper choice of operating parameters the envelope of the series becomes quite distinct. I have enclosed some figures to illustrate this. Figure 1, TPB-10690, shows the Fourier series plot of a 3 MS pulse from 0 cps out to 2,500 cps. I think it will be readily recognized as the spectrum of a rectangular pulse once in time; obtained by drawing the envelope to the Fourier coefficients. The cusp minima are quite distinct at each 340 cps ($=1/2.9$ MS) and the second lobe, centered about 500 cps, is skewed as it should be.

Figure 2, TPB-10691, and Figure 3, TPB-10692, show the effect of making the "duty cycle" longer. Note that in Figure 2 both maxima and minima are well defined. The system noise is about -50 db. Now turning to Figure 3, note that the duty cycle has been doubled, that is it is 10.5/75 instead of 5/75, as in the previous case. As expected, the signal-to-noise ratio is improved by about 6 db, now being approximately -56 db. This, however, is at the expense of detail in the spectrum.

In the case of Figure 1 a 1-cps wide filter was used in the Technical Products Company TP-625 Transient Analyzer System. This filter is narrow enough to avoid integration, that is, only one Fourier coefficient is in the pass band at one time. A second Fourier coefficient is beginning to appear in the pass band below 300 cps, as indicated by the rise of the base line of the graph.

* Received by the Editor March 25, 1960.

† Techno Instrument Co., Los Angeles 38, California.

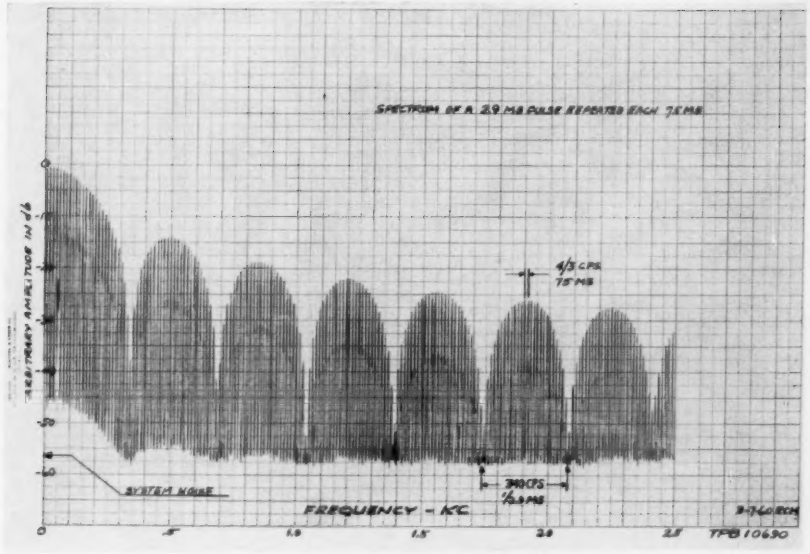

SPECTRUM OF A 2.9 MS PULSE REPEATED EACH 75 MS
ARBITRARY AMPLITUDE IN db
4/3 CPS
75 MS
SYSTEM NOISE
340 CPS
1/2.9 MS
FREQUENCY - KC
0
.5
1.0
1.5
2.0
2.5
3-7-60 RM
TPB 10690

FIG. 1.

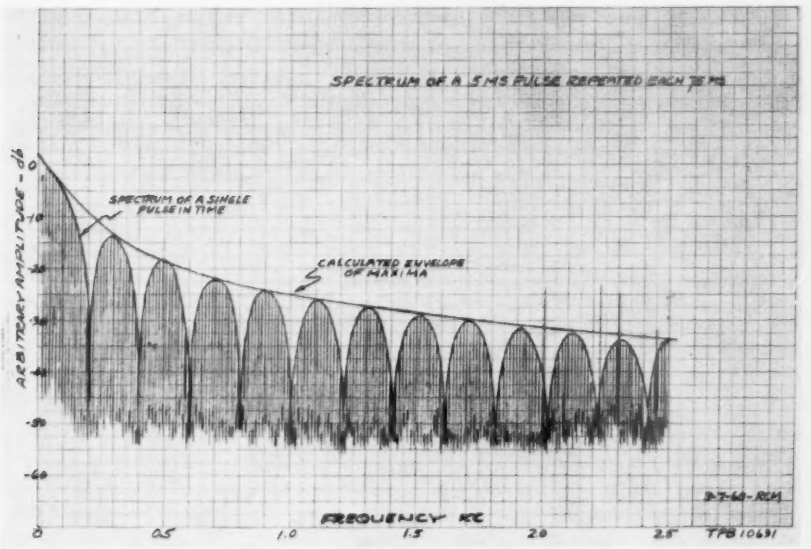

SPECTRUM OF A 1.5 MS PULSE REPEATED EACH 75 MS
ARBITRARY AMPLITUDE - db
SPECTRUM OF A SINGLE PULSE IN TIME
CALCULATED ENVELOPE OF MAXIMA
FREQUENCY KC
0
.5
1.0
1.5
2.0
2.5
3-7-60-RM
TPB 10691

FIG. 2.

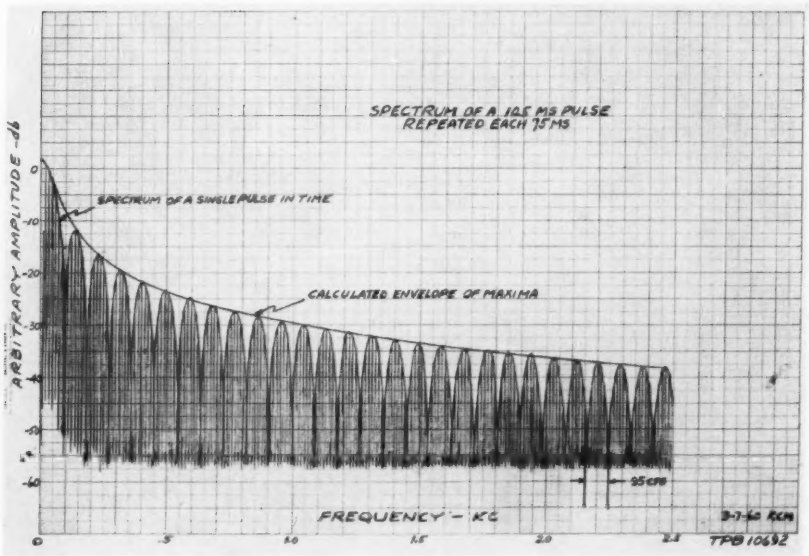


FIG. 3.

Obviously pulses of different shape and longer or shorter duration can be readily analyzed. The rectangular pulse was chosen in this illustration because its spectrum is familiar and readily calculated.

PATENTS

O. F. RITZMANN†

ELECTRICAL PROSPECTING

U. S. No. 2,922,101. F. M. Mayes, Iss. 1/19/60. App. 11/2/53. Assign. Sun Oil Co.

Electrical Prospecting Method and Apparatus. An electrical transient prospecting method in which unbalance of potentials at points spaced equally from the center electrode of a five-electrode in-line array is observed.

GEOCHEMICAL PROSPECTING

U. S. No. 2,921,003. W. D. Rosenfeld. Iss. 1/12/60. App. 9/28/56. Assign. California Research Corp.

Petroleum Prospecting Method. A bacteriological prospecting method in which formation water samples are analyzed for the concentration of hydrocarbon-oxidizing bacteria and anomalously high concentrations used to indicate proximity of petroleum.

GRAVIMETRIC PROSPECTING

U. S. No. 2,921,380. P. H. Savet. Iss. 1/19/60. App. 4/25/56. Assign. American Bosch Arma Corp.

Vertical Indicator. A vertical indicator for an unstable support using a short pendulum that carries an accelerometer whose output is integrated and combined with the pendulum indication.

MAGNETIC PROSPECTING

U. S. No. 2,924,759. K. Maaz. Iss. 2/9/60. App. 10/16/58. Assign. Siemens-Schuckertwerke Aktiengesellschaft.

Hall-Voltage Generating Device. A Hall-effect magnetometer having a resistor mounted perpendicular to the Hall plate and connected in series with the Hall electrodes, the resistor being made of a magnetic-field responsive material whose temperature coefficient compensates the effect of temperature on the Hall-effect voltage.

RADIOACTIVITY PROSPECTING

U. S. No. 2,922,886. J. L. Putman. Iss. 1/26/60. App. 11/21/53 and 11/22/54. Assign. U.S.A.

Method and Apparatus for Testing the Presence of Specific Atomic Elements in a Substance. A method of detecting specific elements in a flow stream or in well logging in which a polonium-beryllium neutron source is used and prompt gamma rays from the well wall or material to be analyzed are detected by means of a scintillation counter whose pulses are analyzed by multi-channel pulse-height analyzers and the outputs recorded.

U. S. No. 2,926,271. J. M. Brinkerhoff, W. C. Hadley, V. E. Ragosine, and J. W. Shearer. Iss. 2/23/60. App. 7/20/53. Assign. Tracerlab, Inc.

Apparatus for Producing Neutrons. A neutron source comprising a discharge tube containing a heavy isotope of hydrogen at low pressure and two disk-shaped electrodes to which breakdown potential is applied, the pressure and voltage being adjusted to maintain the discharge so that collisions occur between ions and neutral atoms of the hydrogen isotopes present.

† Gulf Oil Corporation, Patent Department.

SEISMIC PROSPECTING

U. S. No. 2,920,306. F. J. Feagin and C. R. Wischemyer. Iss. 1/5/60. App. 4/12/54. Assign. Jersey Production Research Co.

Correlator for Zero Crossing Pulses Obtained from Seismograms. A system of correlating seismograms by generating a pulse each time the trace crosses the zero axis and shifting the resulting pulse traces until the best fit between pulse traces is obtained.

U. S. No. 2,920,307. A. A. Chernosky. Iss. 1/5/60. App. 7/19/54. Assign. Jersey Production Research Co.

Variable Gap Reluctance Transducer. A reluctance-type geophone having two semi-cylindrical annular magnets made of a soft magnetic material separated by a very small air gap by means of stiff spring extensions at the ends of the magnets, and a toroidal coil wound on the magnets.

U. S. No. 2,920,308. P. S. Williams. Iss. 1/5/60. App. 7/19/55. Assign. Jersey Production Research Co.

Geophone. A pancake-shaped geophone having a mercury-type reversing switch or using two independently suspended coils one of which is made inoperative by a gravity-actuated clamp so that the geophone phasing is always the same regardless of which face of the geophone is in contact with the ground.

U. S. No. 2,920,523. J. F. Barco and D. E. Albon. Iss. 1/12/60. App. 6/4/57. Assign. Airmite-Midwest Inc.

Method of Charging Water-Filled Blast Holes with Ammonium Nitrate and Primer Cartridge Used in Same. A method of loading an irregular water-filled shot hole by using a tubular container into which is placed a primer cartridge of carbon saturated with liquid oxygen and surrounding the container with prilled ammonium nitrate with a primacord fuse running to the primer cartridge.

U. S. No. 2,920,600. K. K. Hori, T. Hori, and M. Hori. Iss. 1/12/60. App. 10/11/56.

Intermittent Exploding Device. A repeating gas exploding gun having a source of gas under pressure that slowly flows into a chamber having a diaphragm, outward flexure of the diaphragm opening a valve that discharges the gas from the chamber into a gun, and return of the diaphragm electrically igniting the gas in the gun.

U. S. No. 2,921,288. J. P. O'Neill and J. S. Leigh. Iss. 1/12/60. App. 3/20/46. Assign. U.S.A.

Underwater Signaling. An underwater sound source having an array of magnetostrictive or piezoelectric transducers and whose directional pattern is varied by selectively switching groups of transducers.

U. S. No. 2,921,477. G. J. Hanggi. Iss. 1/19/60. App. 12/31/56. Assign. Continental Oil Co.

Constant Force Variable Speed Vibrator. A rotating mass vibrator in which the radius of the mass is adjustable during operation, the mass being slidably held on a radial arm by two struts connected to collars that can move axially on the shaft and which rotate in pistons whose position can be hydraulically adjusted.

U. S. No. 2,921,738. J. P. Greening. Iss. 1/19/60. App. 4/18/55. Assign. Phillips Petroleum Co.

Polynomial Multiplier. A cross correlation computer for seismic signals in which the expected reflection wave form is divided into equal intervals and the respective amplitudes applied to a set of condensers, and the seismometer wave similarly applied to a second set of condensers, the signals on the condensers being successively multiplied and summed.

U. S. No. 2,922,070. D. O. Seevers. Iss. 1/19/60. App. 8/24/54. Assign. California Research Corp.

Seismic Signal Analysis with Cathode Ray Storage Tube. A seismogram analyzing system in which

the traces are processed and stored on the recording surface of a charge-modifiable storage tube from which the traces are read off with desired intertrace time variation and recombined and displayed on the screen of a c-r tube.

U. S. No. 2,922,362. W. M. Mullings. Iss. 1/26/60. App. 5/15/58. Assign. The Atlantic Refining Co.

Geophysical Record Stamp Device. A device for printing consecutive numbers adjacent to the timing lines on a seismogram.

U. S. No. 2,922,484. W. T. Kelly and R. J. Clements. Iss. 1/26/60. App. 6/25/56. Assign. Texaco Inc.

Geophysical Exploration. A sequential shooting system in which several vertically spaced charges with detonators are placed in the shot hole, each detonator having a condenser and a pressure-actuated switch which is actuated by the seismic wave from the adjacent charge.

U. S. No. 2,923,366. E. P. Meiners and G. A. Schurman. Iss. 2/2/60. App. 3/7/52. Assign. California Research Corp.

Seismic Prospecting Method. A seismic prospecting system using a plurality of piezo-electric transducers in holes with a coupling medium and energized by a-c to project a seismic wave into the ground, the a-c being suddenly terminated and the transducers switched to connect them to a recorder for recording reflections.

U. S. No. 2,923,367. W. H. Cox. Iss. 2/2/60. App. 10/6/52. Assign. Sun Oil Co.

Method and Apparatus for Seismic Surveying. A seismic detector system using two detectors in a borehole below the weathered layer, one being a nondirectional pressure detector and the other being a bi-directional velocity detector, the outputs of the detectors being added with a phase shift to correct for vertical spacing of the detectors in the borehole.

U. S. No. 2,923,368. R. H. Hopkins. Iss. 2/2/60. App. 6/13/55. Assign. Sun Oil Co.

Method and Apparatus for Seismic Prospecting. A device for plotting reflecting horizons on a scaled drawing and having a flexible arm fastened to a block at the plotted shotpoint with the lower end of the arm carrying a disk calibrated in proportion to the difference in travel time to detectors equally spaced on each side of the shotpoint, the arm being bent into a circular arc so that the indices on the disk are horizontal at the plotted reflection point.

U. S. No. 2,923,904. G. M. Hieber. Iss. 2/2/60. App. 11/18/57. Assign. Gulton Industries, Inc.

Differential Transformer Accelerometer. A suspended-armature impedance-bridge type seismometer whose moving armature is suspended axially of primary and secondary coils and also carries a damping cup in the annular gap of a damping magnet.

U. S. No. 2,923,915. C. B. Vogel. Iss. 2/2/60. App. 12/1/55. Assign. Shell Development Co.

Geophysical Hydrophone. A reluctance-type hydrophone having a free diaphragm that is held in place by the attraction of the transducer magnet and which has a small hole to provide pressure equalization, the unit having oil on both sides of the diaphragm and a compliant air pocket behind the diaphragm.

U. S. No. 2,923,916. J. H. Woodworth. Iss. 2/2/60. App. 4/1/57. Assign. Socony Mobil Oil Co., Inc.

Marine Seismic Transducer System. A marine seismic detector array in which groups of piezo-electric hydrophones are electrically connected to the main cable through an impedance-matching transformer in a cylindrical container strapped to the cable.

U. S. No. 2,924,810. J. M. Horeth. Iss. 2/9/60. App. 4/29/57. Assign. Jersey Production Research Co.

Seismic Trace Translation. A device for reproducing a seismogram to correct for speed variations

in the original recording and having an adjustable step-cam to control the tape speed of the second recording.

U. S. No. 2,925,138. C. H. Becker. Iss. 2/16/60. App. 3/9/56. Assign. Western Geophysical Co. of America.

Method of Geophysical Exploration. A seismic display system in which separate seismograms from a two-dimensional array of geophones are reproduced and recorded in two dimensions on the screen of a storage tube and selected zones read out and displayed on a c-r tube screen.

U. S. No. 2,925,217. G. J. Watt. Iss. 2/16/60. App. 10/25/56. Assign. Sperry Rand Corp.

Sound Wave Ray Tracer. A ray path plotter having a computer with function generators that develop voltages proportional to the velocity and to the product of velocity and velocity gradient, the voltages being resolved into the vertical and horizontal components which are integrated to give depth and range and control the plotter.

U. S. No. 2,926,249. J. P. Lindsey. Iss. 2/23/60. App.3/29/57. Assign. Phillips Petroleum Co.

Normal Density Function Filter. A seismic filter that removes high frequency energy with no phase distortion and whose impulse response has the shape of a normal error curve.

U. S. No. 2,926,331. J. P. Lindsey. Iss. 2/23/60. App. 2/4/57. Assign. Phillips Petroleum Co.

Seismic Exploration. A seismogram processing system in which signals of adjacent traces are clipped to give signals of square wave form and then summed, rectified, and used to control a gate circuit through which rectified signal of one of the individual traces is transmitted, the output of the gate circuit being multiplied by rectified signal of the other trace and rerecorded.

WELL LOGGING

U. S. No. 2,920,204. A. H. Youmans. Iss. 1/5/60. App. 9/4/56. Assign. Well Surveys, Inc.

Apparatus for Simultaneous Detection of Thermal and Epithermal Neutrons. A neutron logging detector having an outer annular chamber with a photomultiplier to detect thermal neutrons, an annular absorber for thermal neutrons, an annular chamber with a photomultiplier to detect epithermal neutrons, and an inner core of an epithermal moderating material.

U. S. No. 2,920,266. J. D. Owen. Iss. 1/5/60. App. 8/8/56. Assign. Phillips Petroleum Co.

Electrical Well Logging. An electric well logging system using a long hollow sonde with external annular electrodes separated by annular rubber fenders with a-c passed between the end electrode and the surface of the ground and the potentials between successive electrodes measured and recorded.

U. S. No. 2,920,267. K. H. Miner. Iss. 1/5/60. App. 1/3/56. Assign. Dresser Industries, Inc.

Apparatus for Identifying Fluids Passing Through a Formation Testing Tool. A tool for recording the electrical resistivity of formation fluid and which has a packer for sealing off a pilot hole at the bottom of a well, a valve that is opened by rotation of the tubing on which the tool is run, and a sealed recorder housing inside the tubing which records the current between two electrodes on the outer surface of the housing.

U. S. No. 2,920,396. J. V. Fredd. Iss. 1/12/60. App. 12/23/57. Assign. Otis Engineering Corp.

Surface Caliper. A calipering device having feeler arms individually mechanically connected to sliders of variable resistance elements so that movement of individual feelers is indicated but simultaneous movement of all of the feelers also varies the position of the resistance element and is not indicated.

U. S. No. 2,921,253. W. Liben. Iss. 1/12/60. App. 1/31/56. Assign. Schlumberger Well Surveying Corp.

Magnetic Devices. An electric logging system in which the source a-c is also fed to the primary of a saturable-core transformer and the emf picked up by the potential electrodes is rectified and fed to the control winding of the transformer whose secondary voltage is indicated.

U. S. No. 2,922,102. F. F. Segesman. Iss. 1/19/60. App. 4/10/56. Assign. Schlumberger Well Surveying Corp.

Electrical Well Logging. A scale-compression system for an electrical resistivity logging device in which a constant potential voltage source is used and a potential proportional to the current is subtracted from the measured potential.

U. S. No. 2,922,103. O. R. Smith. Iss. 1/19/60. App. 7/27/56. Assign. Welex, Inc.

Electrical Resistivity Determination of Well Bore Fluids. A sonde for measuring the resistivity of fluid in a well having an open-ended sleeve of insulating material with annular electrodes on its inside surface.

U. S. No. 2,922,885. C. W. Tittle. Iss. 1/26/60. App. 12/29/53. Assign. Gulf Research & Development Co.

Logging of Energy Distribution. A radio-activity logging apparatus having a detector that produces a pulse whose height is dependent on the energy of the radiation and in which the pulse is displayed on a c-r oscilloscope whose horizontal sweep is triggered by the pulse, the c-r screen being photographed with all but the uppermost horizontal part of the trace masked.

U. S. No. 2,922,889. H. E. Hall, Jr. Iss. 1/26/60. App. 2/17/56. Assign. Texaco Inc.

Well Logging Systems. A pulse transmission system for radioactivity logging in which the original pulses control a hydrogen thyratron producing high-power one-microsecond pulses that can be resolved at the output end of the cable.

U. S. No. 2,923,151. C. J. Engle and S. J. Marwil. Iss. 2/2/60. App. 12/17/56. Assign. Phillips Petroleum Co.

Extracting and Analyzing Gas from Well Drilling Mud. A system for extracting gas from drilling mud by diluting with water and flowing the mud tangentially into the top of a conical cyclone separator and removing mud at the bottom and gas at the top and passing the gas through a drier and analyzer.

U. S. No. 2,923,824. P. W. Martin and R. W. Pringle. Iss. 2/2/60. App. 8/10/53.

X-Ray Analysis of Geological Formations. A well logging method in which the formations are irradiated with high energy X-rays or gamma rays and with a scintillating crystal mounted on a protuberance on the wall of the sonde pressed against the borehole wall, observing the characteristic secondary X-rays and recording their spectral distribution.

U. S. No. 2,923,825. G. Swift. Iss. 2/2/60. App. 2/8/54. Assign. Well Surveys, Inc.

Apparatus for Neutron Well Logging. A neutron logging apparatus having a neutron source that also emits gamma rays and having spaced from the source a detector with a cylindrical shield of lead having a thickness of from 0.5 to 1.5 cm.

U. S. No. 2,924,289. M. C. Ferre. Iss. 2/9/60. App. 12/31/54. Assign. Schlumberger Well Surveying Corp.

Methods and Apparatus for Exploring Earth Formations. A well logging method that measures the shear modulus of formations by generating an alternating pressure in a region of the hole by using

three electro-acoustic transducers whose phases are adjusted to produce zero fluid flow at points above and below the middle transducer, and measuring the pressure and volume change of the region.

U. S. No. 2,924,432. J. J. Arps and S. A. Scherbatskoy. Iss. 2/9/60. App. 5/8/56.

Earth Borehole Logging System. A device for multi-channel logging while drilling having a mud-pressure actuated stepping switch so that the type of log obtained can be changed by the operator by momentarily reducing circulation pressure.

U. S. No. 2,925,251. J. J. Arps. Iss. 2/16/60. App. 3/5/54.

Earth Well Borehole Drilling and Logging System. A system of logging while drilling in which an electrical system in the drill collar actuates a mud-flow valve at a frequency dependent on resistivity, and the mud-flow at the bit actuates a low-frequency valve so that signals from a pressure transducer at the surface will indicate the resistivity of the formation and evidence of a drill string leak.

U. S. No. 2,925,551. F. F. Segesman. Iss. 2/16/60. App. 3/13/56. Assign. Schlumberger Well Surveying Corp.

Well Logging Systems. An electric logging system in which current to auxiliary focusing electrodes is controlled from the potential gradient at control electrodes between the main current electrode and the auxiliary electrode, and in which the potential at the control electrode is observed when the main current is interrupted but the focusing current is still turned on, so as to simultaneously measure formation resistivity remote from the borehole and close to the borehole.

U. S. No. 2,925,660. G. M. Raulins. Iss. 2/23/60. App. 12/3/57. Assign. Otis Engineering Corp.

Feeler Head Assembly. A device for detecting and recording areas in which an electrically insulating coating has been worn off the inside of tubing, and in which the feelers mechanically detect tubing joints and also serve as contactors to detect bare spots.

U. S. No. 2,926,259. J. T. Dewan. Iss. 2/23/60. App. 9/23/53. Assign. Schlumberger Well Surveying Corp.

Method and Apparatus for Analyzing Earth Formations. A well logging apparatus that extracts a sample of formation fluid from the wall of the borehole and exposes the sample to neutrons and measures the induced gamma-ray activity, provision being made to flush the sample chamber with pure water for a reference measurement.

(See also patents 2,922,886 and 2,926,271 listed under Radioactivity Prospecting.)

MISCELLANEOUS

U. S. No. 2,920,320. K. F. Ross. Iss. 1/5/60. App. 12/3/54.

Radiolocation System. A radiolocation system in which the transmitter sends out two carrier waves whose reflections are picked up at two spaced receivers and the received waves compared with the transmitted waves so that two direction indications are obtained for the respective reflections.

U. S. No. 2,920,321. H. Gabler. Iss. 1/5/60. App. 12/28/55. Assign. Maximilian Waechtler.

Navigational Position Finding Apparatus. A radio navigation system in which the angles to three fixed transmitters are simultaneously indicated on a c-r tube screen by means of a radio direction finder, the three transmitters being keyed by synchronously driven timers so that each transmitter's operation and its indication is independent of the others.

U. S. No. 2,921,301. V. F. Cartwright. Iss. 1/12/60. App. 7/6/56. Assign. The Ralph M. Parsons Co.

Distance Measuring System. A system for measuring distance between two stations in which one station transmits a signal on a first carrier frequency which is picked up at the other station and re-transmitted on a second carrier frequency, the frequency of signal oscillation being a measure of the distance between the stations.

Selected List of U. S. Patents

Issued During January and February of 1960

Patent No.	*Subject**	*Patent No.*	*Subject**	*Patent No.*	*Subject**
2,919,574	12, 140	2,921,288[a]	108, 436	2,922,884	308
2,919,578	68	2,921,294	224	2,922,885[a]	304
2,919,579	200	2,921,301[a]	312	2,922,886[a]	304, 308
2,919,580	460	2,921,304	316, 324	2,922,887–888	308
2,919,583–586	16	2,921,380[a]	180	2,922,889[a]	304, 516
2,919,605	68	2,921,465–466	12, 140	2,922,911	168
2,919,646	48	2,921,467	148	2,922,947	228
2,919,856–857	68	2,921,469–470	200	2,922,949	228
2,920,140	484	2,921,471–472	16	2,922,950	16
2,920,146	224	2,921,477[a]	76	2,922,966–967	12
2,920,148–149	224	2,921,519	136	2,922,999	12
2,920,200	236	2,921,522	32, 136	2,923,000–001	16, 312
2,920,204[a]	308	2,921,738[a]	68	2,923,002	16
2,920,207	308	2,921,739–740	68	2,923,003–005	316
2,920,266[a]	116	2,921,753	224	2,923,151[a]	252
2,920,267[a]	36, 508	2,921,757	16	2,923,153	288
2,920,269–270	140	2,921,795	224	2,923,154–155	148
2,920,298–299	428	2,921,989–991	224	2,923,156–157	200
2,920,306[a]	352	2,921,993	484	2,923,159	412
2,920,307[a]	376	2,922,036	308	2,923,161	16
2,920,308[a]	376	2,922,070[a]	352	2,923,366[a]	360
2,920,320[a]	312	2,922,087	308	2,923,367[a]	360
2,920,321[a]	312	2,922,095	68	2,923,368[a]	352
2,920,379	224	2,922,101[a]	120	2,923,380	224
2,920,396[a]	44	2,922,102[a]	116	2,923,466	68
2,920,483	148	2,922,103[a]	116	2,923,468	68
2,920,484	200	2,922,106	224	2,923,470	68
2,920,487	288	2,922,140	484	2,923,477	68
2,920,523[a]	136, 360	2,922,154–155	316	2,923,530	392
2,920,600[a]	136	2,922,159	16, 224, 444	2,923,586	308
2,920,601	200	2,922,224	16	2,923,642	224
2,920,604	12	2,922,225	444	2,923,779	224
2,920,617	484	2,922,227–228	216	2,923,780	224, 484
2,920,826	68	2,922,231	224	2,923,782–783	484
2,920,828	68	2,922,308	316	2,923,822	236
2,920,880	428	2,922,362[a]	352, 368	2,923,824[a]	304
2,920,930	324	2,922,484[a]	8, 360	2,923,825[a]	304
2,921,003[a]	172	2,922,578–579	68	2,923,861	16
2,921,125–126	324	2,922,632	4	2,923,885	160
2,921,134	484	2,922,633	492	2,923,889	68
2,921,198	236	2,922,655	224	2,923,904[a]	4
2,921,253[a]	116	2,922,686–689	324	2,923,915[a]	376
2,921,282	428	2,922,844	308	2,923,916[a]	376

* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

Patent No.	Subject*
2,923,932	16, 312
2,923,933	316
2,924,097	148
2,924,104	16
2,924,173	48
2,924,234	200
2,924,289[a]	8
2,924,381	68
2,924,383–384	68
2,924,385	16, 68
2,924,386	68
2,924,432[a]	208, 516
2,924,462	224
2,924,498	188
2,924,499	324
2,924,668–669	224
2,924,709	68
2,924,711	68
2,924,713	196
2,924,718–720	308
2,924,759[a]	232
2,924,810[a]	352
2,924,820	312
2,924,822	312
2,924,882	68
2,924,885	16
2,924,886	216
2,924,894	68
2,924,967	428
2,924,970	428
2,924,972	148
2,924,973	200
2,924,978	16
2,925,007	288
2,925,008	324
2,925,138[a]	352, 360
2,925,217[a]	12, 352
2,925,220	68
2,925,251[a]	208
2,925,279	324
2,925,281	324
2,925,308–312	324
2,925,327	168
2,925,503	76, 484, 492
2,925,509	308
2,925,544	324, 484
2,925,551[a]	116
2,925,552	140, 228
2,925,572	460
2,925,573	428
2,925,576	428
2,925,580	108
2,925,581	12
2,925,597	316
2,925,660[a]	44
2,925,662	216
2,925,731	428
2,925,736	16
2,925,775	48
2,925,956	68
2,925,967	16
2,926,018	224
2,926,058–059	324
2,926,219–220	224
2,926,243	316
2,926,249[a]	348
2,926,251	236
2,926,253	196
2,926,259[a]	304
2,926,261	308
2,926,271[a]	308
2,926,320	460
2,926,331[a]	352
2,926,338	68, 224
2,926,341	68

REVIEWS

REVIEWS COMMITTEE

CARL H. SAVIT, Chairman, Western Geophysical Company of America, Los Angeles, California
JAMES AFFLECK, Gulf Research & Development Company, Pittsburgh, Pennsylvania
WILLIAM L. BASHAM, Standard Oil Company of California, La Habra, California
F. G. BLAKE, California Research Corporation, La Habra, California
PIERRE L. GOUPILLAUD, Continental Oil Company, Ponca City, Oklahoma
ROLAND G. HENDERSON, U. S. Department of the Interior, Washington 25, D. C.
HYMAN KAUFMAN, McGill University, Montreal, Canada
NORMAN H. RICKER, The University of Oklahoma, Norman, Oklahoma
JOSHUA L. SOSKE, Stanford University, Stanford, California
S. H. WARD, University of California, Berkeley, California
ISIDORE ZIETZ, U. S. Department of the Interior, Geophysics Branch, Washington 25, D. C.

CONTENTS

The Earth, Its Origin, History and Physical Constitution, Sir Harold Jeffreys, By *P. C. Wuenschel.* 959
Overvoltage Research and Geophysical Applications, James R. Wait, By *J. E. White*..... 960
Stratigraphic Principles and Practice, J. Marvin Weller, By *Joshua L. Soske*..... 961
Scandinavian Electromagnetic Prospecting, Frank C. Frischknecht, By *S. H. Ward*..... 962
Airborne Radiometric Survey of Portion of the Olary Province, J. L. Harris, By *S. H. Ward*..... 962
On the Source Data Used in the Paper "Geology and Oil Prospects of the Northern Black Sea Area and Northwestern Azov Sea Area," N. G. Mikhaylova, By *Carl H. Savit*..... 963
Patent Office Rules and Practice, Irving Seidman and Lester Horwitz, By *Carl H. Savit*..... 963
Operational Calculus, Jan Mikusinski, By *Hyman Kaufman*..... 964
Mathematics for Communication Engineers, S. J. Cotton, By *Richard J. Runge*..... 965

The Earth, Its Origin, History and Physical Constitution, Sir Harold Jeffreys, F.R.S., Fourth Edition, New York, Cambridge University Press, 1959, 401 pp., $13.50.

Sir Harold Jeffreys' classic book *The Earth* has as its objective the quantitative comparison of fact with theory. The theory of the physical constitution of the earth is conformed to the facts observed in seismology, astronomy, geodesy and tectonophysics—four of the branches of earth science in which the author is an outstanding authority and to which he has contributed continuously for the past 45 years. The book also includes chapters on the age of the earth, the earth's thermal history, the origin of the earth's surface features and a group of special problems, two of which are of timely interest; namely, polar wandering and continental drift.

With the present rate of growth of geophysics it is becoming increasingly more difficult to incorporate under a single cover the breadth of coverage that the author has achieved and still maintain the completeness that characterized the earlier editions. In the preface to this fourth edition the author points out that because of this growth many important contributions could only be treated briefly. For example, terrestrial magnetism has been given only one page. Crustal structure as determined by surface waves is far from complete—the most recent reference cited is 1948. The use of earth satellites to determine the figure of the earth has been given a scant eleven lines. The treatment of tidal friction on the other hand has been considerably revised. An estimate of its magnitude has been made possible from the damping of the 14-monthly variation of latitude. The sections on continental drift and polar wandering have been extended. The author does not waver from his conviction that the rigidity of the ocean basins prevents continental drift, Wegenerian style, while he considers polar wandering—that is movement of the crust as a whole relative to the axis of rotation—as being quite possible.

The comments made above relative to the completeness of certain sections of the book suggest that it may be limited as a reference to recent information in some fields; they are not intended to minimize the basic understanding of the earth that the author has given us.

The fourth edition is enlarged over the third by the addition of many new developments but maintains the over-all plan of the preceding edition.

It is superfluous for a reviewer to recommend a book that is in its fourth edition and one that is written by the foremost theoretician of our time.

P. C. WUENSCHEL
Gulf Research & Development Company
Pittsburgh, Pennsylvania

Overvoltage Research and Geophysical Applications, James R. Wait, Pergamon Press, New York and London, 1959, 158 pp., $9.00.

Interest in the phenomenon of overvoltage (or induced polarization) is evidenced by recent articles in GEOPHYSICS and continuing research on the subject. During the last decade, a group at Newmont Exploration Limited has been extremely active in developing equipment for mineral exploration using induced polarization and in promoting a fuller understanding of the phenomenon. This monograph reports the results of their work, so that other groups might benefit from the knowledge which was not easily attained.

In the opening chapter, A. A. Brant gives a concise history of the research and development at Newmont, which was carried out under his supervision. The method has been used in Arizona, Peru, Canada, Mexico, South Africa, South-west Africa, and Rhodesia. Dr. Brant concludes that, if used in the proper geologic environment, the overvoltage method can be a powerful tool for detecting scattered sulfides. In older rock areas, however, background effects become larger and anomalies are frequently spurious.

In Chapter 2, H. O. Siegel treats a homogeneous solid in which the passage of a current sets up current dipoles oppositely oriented, giving rise to a bulk effect defined as "chargeability." Seigel derives expressions for the overvoltage response characteristics of heterogeneous media, and theoretical curves are compared with field data for the Werner electrode configuration on a two-layered earth.

In Chapter 3, J. R. Wait explains at least in a qualitative way the main features of overvoltage response in terms of a homogeneous medium loaded with conductive spherical particles, each coated with a dielectric film.

In Chapter 4, J. R. Wait relates the transient overvoltage response of an electrode array to the frequency-dependent conductivity found to be characteristic of mineralized regions. Inter-wire coupling effects are also discussed briefly.

In Chapter 5, L. A. Collett describes equipment and presents laboratory data on induced polarization in mineralized and non-mineralized rock specimens.

In Chapter 6, J. R. Wait describes the detailed analysis of decay curves on rock specimens, and N. F. Ness discusses the corresponding analysis for frequency response data of mineralized and non-mineralized samples.

In Chapter 7, G. V. Keller imagines the induced polarization to result from a distribution of relaxation times, and he analyzes the Newmont data in terms of the superposition of simple exponential forms. Distributions of relaxation times for principal rock types are plotted.

In Chapter 8, K. A. Ruddock describes field equipment very briefly. Current pulses of several amperes are supplied for several seconds at a time, spaced by off-current periods, and alternating in direction. Some field procedures and precautions are mentioned.

In Chapter 9, R. W. Baldwin appraises the success of the overvoltage method, citing experience in Arizona, Peru, Manitoba, and South Africa. Mention is made of extraneous responses due to non-sulfides.

In Chapter 10, V. Mayper, Jr. discusses in some detail the "normal effect," a polarization signal widely encountered which may obscure the effects due to sulfide minerals. "The conclusion is drawn that, of the hypotheses so far advanced, the only ones still allowable are that the effect is due to a current-induced disequilibrium in the electrochemical properties of particles in the rock pores (probably ion exchange in clay), or that it is due to the presence of very slight true conductivity in some 'non-conducting' minerals. Hypotheses involving electro-kinetic effects, air bubbles or surface conduction have been rejected."

This monograph is a significant addition to the literature on polarization phenomena in earth materials. Newmont Exploration is to be commended for making public their achievements toward a more complete understanding of induced polarization phenomena and their experience with the overvoltage method as an exploration tool.

J. E. WHITE
The Ohio Oil Co.
Littleton, Colorado

Stratigraphic Principles and Practice, J. Marvin Weller, Harper & Brothers, New York, 1960, 725 pp., $10.00.

Considering the 18 chapters divided into four parts, this book represents an astoundingly large effort by the author to write a comprehensive treatise covering stratigraphy and its many related subjects. The book appears to surpass the level of an ordinary course textbook on stratigraphy by possessing the scope of a handbook on the subject. The author's definition of stratigraphy is of sufficient interest to be repeated here: "Stratigraphy is the branch of geology that deals with the study and interpretation of stratified and sedimentary rocks and with the identification, description, sequence, both vertical and horizontal, mapping, and correlation of stratigraphic rock units."

Under the main subject of stratigraphy, Historical Geology, Tectonics, Geological Field Mapping, Paleoecology, Physical Geology, Sedimentary Petrology and Sedimentology are pungently discussed. This list of specialities covers for the most part the whole of "soft rock geology." Probably the prejudices of the reviewer are the basis of the notion that the author makes a moderately strong effort throughout the book to regard most of the specialities of soft rock geology as subdisciplines of stratigraphy. This approach may, in fact, be the correct representation, but many scholars of Historical Geology for example would strongly object to being called stratigraphers.

Under the author's definition of stratigraphy, the principles and practices of the methods used by exploration geophysists employing the seismograph, gravity meter or the magnetometer, to map and correlate subsurface stratigraphic rock units, may also be regarded as subdisciplines of stratigraphy. The reviewer merely makes this comment for the benefit of exploration geophysicists, without any thought of criticizing the author for the omission.

One cannot escape the fact that the author's presentation reflects an attempt to place in one handy volume the basic principles and practices of the significant specialties of soft rock geology. It is a demonstration of the very broad geological experience and knowledge of the author. The work is not confined to the specialty of stratigraphy, but is directed toward wider aspects and uses of the branch of geology. Probably less than one third of the book deals specifically with stratigraphy in the narrower sense.

In fulfilling the purpose to which this book is dedicated, it is quite complete in subject matter, adequately and interestingly presented, and abundantly supplied with 273 carefully drawn informative figures. The excellent format represents the execution of plans undoubtedly derived from much painstaking care and a large amount of forethought.

Bibliographies are appended to each chapter. It is within these bibliographies that a scholarly reader may note a serious weakness in the book. The references cited are disturbingly confined to American sources with practically no mention of any works of Europeans in the field or related fields to stratigraphy. The reasons for these omissions are not obvious to the reviewer.

Part I consists of three chapters dealing with concepts of stratigraphy and geologic time, the development of stratigraphy as a speciality and the standard geological systems. Part II is entitled Materials of Stratigraphy. It contains six chapters: (1) Classification and Composition of Sediments and Rocks, (2) Textures, Structures and Colors of Sediments and Rocks, (3) Physiography of Sediments, (4) Paleoecology, (5) Tectonics, and (6) Interpretation of Sedimentary Rocks. Part III is entitled Stratigraphic Bodies and Relations. This part contains seven chapters: (1) Stratification and Vertical Sequence, (2) Unconformities, (3) Stratigraphic Classification, (4) Stratigraphic Nomenclature, (5) Lateral Variation and Facies, (6) Correlation, and (7) Historical Geology. Part IV is an appendix consisting of two chapters: (1) Graphic Representation and (2) Field Work and Geologic Mapping.

The author holds that an understanding of all these topics is important for the formulation of the concepts of stratigraphy. The reviewer is not so clear on this point; however, he is confident that an understanding of all these subjects is of utmost importance to geophysicists in petroleum exploration. The reading of all of Part I, Chapter 8 (Tectonics), and Part IV (Appendix) dealing with representation of stratigraphic data and geologic mapping, should be on the must-read list for exploration geophysicists.

The technical scholar of mature development in the field of soft rock geology may find portions of the book lacking in scholarly approach. The reviewer, however, is not disappointed with any of the editorial characteristics of the text. He is favorably impressed with the scholarship of the author and the prestige of the publisher.

The volume possesses characteristics of a good reference book of long usable life. It will find a large number of appreciative readers among geologists and geophysicists. Younger people in college interested in practically any phase of soft rock geology will do well to read this book.

JOSHUA L. SOSKE
Stanford University
Stanford, California

Scandinavian Electromagnetic Prospecting, Frank C. Frischknecht, *Mining Engineering*, Vol. 11, 1959, pp. 932–937.

This review of the Scandinavian E.M. (Electromagnetic) systems by a prominent member of the Geophysics Division of the U.S.G.S. has been carefully prepared. It should be emphasized, however, that all comments therein pertain specifically to the Scandinavian systems and should not be considered necessarily applicable to systems of other origin.

Mr. Frischknecht's procedure of dividing the Scandinavian systems into two groups of Fixed-Source Methods and Moving-Source Methods is logical and aids the discussion. The principles, basic interpretative procedures, and equipment descriptions of four fixed-source and four moving-source techniques are given (including the familiar Turam or two-coil and Slingram or sending plus receiving coil systems).

The high resolution of the moving-source systems and the great depth of exploration of the fixed-source systems make each suitable for its own assigned tasks. The comment by the author that one group of systems produces results which are more difficult to interpret than the other seems odd insofar as interpretation of any electromagnetic data is based upon comparison of field results with those from model experiments, always, of course, in the light of accumulated field experience. Minor modifications of field techniques should minimize such difficulties and render moving-source methods as easy to interpret as fixed-source methods. Insofar as the moving-source techniques offer the definite advantage that each buried conductor is assessed equally and in an unbiased fashion, they often are considered first for reconnaissance surveys. The fixed-source methods, on the other hand, are most desirable where great depth of exploration and high sensitivity to poorly conductive bodies are required despite the fact that conductors nearest the source give rise to anomalies of amplitudes different to those at a distance (i.e. the anomalies are biased in favor of one conductor or another).

This article will be of particular value to the geophysicist familiar with one or more North American E.M. systems because he will benefit from the generally broad knowledge of the use of many systems displayed by Scandinavian geophysicists.

S. H. WARD
University of California
Berkeley, California

Airborne Radiometric Survey of Portion of the Olary Province, J. L. Harris, *Mining Review, Department of Mines, South Australia*, No. 105, 1958, pp. 10–22.

As stated in a preface, "contained in this 'Mining Review' are reports of topical interest dealing with mineral resources investigations carried out by the Geological Survey and other branches of the

(South Australian) Department of Mines during the period July to December 1956." Its main point of interest to readers of this journal is the demonstration that the technique of "rim flying" as applied in uranium exploration on the Colorado Plateau may be adapted to other types of terrain.

One innovation employed during the radioactivity surveys reported on in "Mining Review" 105 is the technique of adjusting sensitivity of the instrument to allow for variations in instrument gain and atmospheric absorption. This is achieved by flying over a given radioactive source at constant elevation prior and subsequent to each flight and normalizing the results from each flight accordingly.

Despite the fact that the surveys were flown at terrain clearance ranging from tree top level to 100 ft, the author draws the conclusion—based on ground checks of hundreds of anomalies—that mass effect gave rise to most of the anomalies recognized. It should be mentioned here that a relatively low signal-to-noise ratio of less than 2 to 1 was employed in selection of "anomalies." This procedure does not appear to be justifiable even though the author goes to considerable effort to attempt to justify it (largely on the basis of small area of anomaly sought). Flight line intervals were close, being about 50 yards.

Surprisingly, the mass effect was attributed mostly to thorium, and not potassium, in granites. A brief description of the results of ground-checking most of the anomalies is given. The author states that "the background from the surrounding Archean granitic rock types is much higher and far more variable from place to place than in the Colorado sedimentary areas with the very frequent resultant swamping of the radiation from a small or point source. This overwhelming effect of the background becomes more pronounced with height but still has an effect even at low altitudes as was evident during this survey." This should not be surprising considering the anomaly threshold adopted.

S. H. WARD
University of California
Berkeley, California

On the Source Data Used in the Paper "Geology and Oil Prospects of the Northern Black Sea Area and Northwestern Azov Sea Area," N. G. Mikhaylova, *Petroleum Geology*, Vol. 2, 1958 (English edition published 1960), pp. 988–989.

A previous publication by other authors used reflection seismic data to provide an estimate of the depth of the sedimentary section in a part of the Black Sea area. Mikhaylova notes that the velocities deduced from reflection data do not agree within reasonable limits of error with those obtained from an acoustic log of a subsequent well. An extensive analysis of velocities derived from normal moveouts of the original reflection data offers conclusive proof that the overwhelming majority of reflections below a time of 1.3 seconds are multiples.

Although the present paper is extremely short, the evidence presented is indicative of clear thinking and a great deal of careful work.

CARL H. SAVIT
Western Geophysical Company of America
Los Angeles, California

Patent Office Rules and Practice, Irving Seidman and Lester Horwitz, Matthew Bender & Company, Albany and Clark Boardman Company, New York, 1959, vi+712+676 pp. $30.00.

Originally published in 1949 under the authorship of the late Leon Amdur, *Patent Office Rules and Practice* has been reissued in completely revised form under new authorship. Revision of this fundamental reference work in the patent field has been urgently needed. The revised Rules of Practice first promulgated in 1949 and the new codification of patent law, which has governed patent procedure since January 1, 1953, have given rise to numerous revisions of patent practice and to new lines of interpretative decisions. Seidman and Horwitz's new compendium thus fills a most pressing need.

Organized in conformity with the Rules of Practice, the present work is divided into sections whose numbers correspond to those of the Rules. Each section contains a comprehensive discussion

of the rule to which it applies together with a collection of appropriate citations. Each citation is quoted or abstracted in the body of the text and is identified in a footnote. Extensive citations containing matter not necessary to the exposition of the text are, however, quoted at length in footnotes. This type of organization is excellently suited both to use for reference purposes and to reading for general background. The reader for background need only confine his attention to the text leaving the footnotes for those who seek detailed information on specific points.

In those cases in which modern practice differs from the older practice, the authors generally present brief statements of the older procedures or decisions in comparison with modern procedures and decisions. Such presentations are especially valuable when reviewing older patents and their file histories.

In the course of updating the text, whole new sections have been added. An example of a particularly extensive addition arising from revised practice is the discussion of Modern Ex Parte Card and Card Practice. This section deals with the copying of claims from an issued patent for the purpose of invoking an interference. The extent to which the copied claims may differ from the claims in the patent in order that they may be applicable to the invention of the application is explored in comprehensive detail. Similarly extensive expositions occur throughout the text.

While *Patent Office Rules and Practice* is absolutely essential to all practicing patent attorneys and agents, it should also prove most useful to all who work with patents and particularly to those who control the patent activities of corporations. The clear language and simple organization of this book contribute mightily to its use by the non-specialist. Answers to most of the questions which arise in day-to-day patent activity are clearly and readily available.

If criticism is to be leveled at this book, it must be directed to the mechanics of publication. It is hard to believe that many sections have been proofread at all. Lines are interchanged or even omitted, typographical errors abound, even to the extent that occasionally some considerable effort must be devoted to deducing the meanings of the authors. A minor irritation arises from the pagination which is broken at 712 to begin anew at 1,001. It appears that at some stage in the publication it was intended to issue two volumes rather than one, the first volume covering rules 1 to 199 and the second, the remainder of the rules. All pages of the text, however, are presented in one 3-inch looseleaf binder.

Those who work with patents will find that the 15 or 20 hours require to read this book can hardly be better spent.

CARL H. SAVIT
Western Geophysical Company of America
Los Angeles, California

Operational Calculus, Jan Mikusinski, Pergamon Press, New York and London, 1959, 495 pp., $15.00.

The first edition of this book (in Polish), which appeared in 1953, was acclaimed as an exceptionally lucid account of an important segment of contemporary mathematical analysis. The present English edition differs from the first mainly in the addition of a large Appendix which includes proofs of theorems omitted in the earlier edition, new results, and the relation of the operational calculus to abstract algebra, theory of distributions, and Banach spaces. The book consists of seven parts: Operational Algebra, Sequences and Series of Operators, Operational Differential Calculus, Differential Equations with Constant Coefficients, Integral Operational Calculus, Appendix, and Formulae and Tables.

The presentation is that of the author's own systematic development of the Heaviside calculus, based on the central concept of a convolution of two functions. An illuminating comparison with the Laplace transform technique is given. The text is well supplied with applications, including lengthy chapters on electric circuits, vibrating strings, and the heat and transmission line equations.

This book can be especially recommended to those who make frequent use of transform techniques, and who want to become familiar with the more searching aspects of the operational calculus.

HYMAN KAUFMAN
McGill University
Montreal, Canada

Mathematics for Communication Engineers, S. J. Cotton, The Macmillan Company, New York, 1959, 245 pp., $7.50.

This book is intended for engineers, particularly communication engineers, and others desiring an introduction to certain branches of applied mathematics, which is not presented on a high level. In 229 pages of text, the author attempts to cover a wide field of applied mathematics which includes, for the most part, various branches of analysis. As a consequence of this, the treatment of any one subject is brief and sketchy. However, it would seem as though such a text would be adequate if the reader was reviewing a mathematical subject he had previously studied more thoroughly.

The first six chapters constitute a review of elementary mathematics including integral and differential calculus, algebra, determinants, trigonometry, and some elementary complex variable. The chapter on applications of mathematics to the theory of communication networks is perhaps the best in the book with respect to completeness and detail. Another chapter on harmonic analysis using integral transform theory is quite brief and not too commendable. A brief chapter on functions of a complex variable is presented as well as a chapter on vector analysis along with two very abbreviated chapters on the special higher functions and theory of probability. The treatment of special higher functions is very brief and serves only to give the reader a taste of this subject. The chapter on probability theory is similarly without depth.

In many sections, the book reminds one of a handbook of formulas and rules, and these are, for the most part, sketchy and brief.

RICHARD J. RUNGE
California Research Corporation
La Habra, California

PUBLICATIONS RECEIVED

BOOKS

Inventions, Patents and their Management, by Alf K. Berle and L. Sprague de Camp, D. Van Nostrand Co., Inc., Princeton, N. J., $12.50

Space Technology, edited by Howard Seifert, John Wiley & Son, Inc., New York, $22.50.

Scientific Russian, by George E. Condoyannis, John Wiley & Son, Inc., New York, $3.50.

The Geological Evolution of North America, by Thomas H. Clark and Colin W. Stearn, the Ronald Press Company, New York, $7.50.

Elements of Crystallography and Mineralogy, by F. Alton Wade and Richard B. Mattox, Harper & Brothers, New York, $7.50

Invertabrate Paleontology, by William H. Easton, Harper & Brothers, New York, $10.00.

Introduction to Space, by Lee A. DuBridge, Columbia University Press, New York, $2.50.

Optical Crystallography, 3rd edition, by Ernest E. Wahlstrom, John Wiley & Sons, Inc., New York, $8.50.

Physical Geography, 2nd edition, by Arthur N. Strahler, John Wiley & Sons, Inc., New York, $7.50.

Elements of Petroleum Reservoirs, by Norman J. Clark, Society of Petroleum Engineers of AIME, Dallas.

Modern Probability Theory and Its Applications, by Emanuel Parzen, John Wiley & Sons, Inc., New York, $10.75.

PERIODICALS

American Journal of Science, v. 258, nos. 4 & A (April, 1960).
Annales de Geophysique, v. 16, n. 1 (1960).
Annali di Geofisica, v. 12, n. 4 (Oct.–Dec., 1959).
Boletin de la Asociacion Mexicana de Geologos Petroleros, v. 11, nos. 9 & 10, (Sept.–Oct. 1959).
Bulletin of the Earthquake Research Institute, v. 37, part 4 (Dec., 1959).
Bulletin (Izvestiya) english edition, nos. 1 & 2 (Jan. & Feb. 1960).
Bulletin of the Seismological Station, nos. 36 & 37 (July–Dec. 1958).
Deutsche Hydrographische Zeitschrift, v. 12, n. 5 (1959).
Disaster Prevention Research Institute Bulletin, n. 30 (Dec., 1959).
Economic Geology, v. 55, n. 2 (April, 1960).
Erdol Und Kohle, v. 13, n. 3 (March, 1960).
Geofysiske Publikasjoner, v. 21, n. 4 (Oct., 1959).
Geoloski Glasnik, (1958).
Geophysical Abstracts, v. 179 (Oct.-Dec., 1959).
Geophysical Digest, v. 7, nos. 1 & 2 (Jan. & April, 1960).
Geophysical Notes, v. 12, n. 1 (1959).
Geophysical Prospecting, v. 8, n. 1 (March, 1960).
Gerlands Beitrage Zur Geophysik, v. 68, n. 6 (1959).
Journal of Geophysical Research, v. 65, nos. 3 & 4 (March & April, 1960).
Journal of Petroleum Technology, v. 12, nos. 3 & 4 (March & April, 1960).
Mines Magazine, v. L, n. 4 (April, 1960).
Mining Engineering, v. 12, n. 3 (March, 1960).
Physics Today, v. 13, nos. 3 & 4 (March & April, 1960).
Rocznik, Annales de la Societe Geologique de Pologue, v. 29, n. 3 (1959).
The Science Reports of the Tohoku University, v. 11, n. 2 (Sept., 1959).
Tellus, v. 12, n. 1 (Feb., 1960).
Transactions American Geophysical Union, v. 41, n. 1 (March, 1960).

MEMORIAL

DR. DONALD THOMAS GERMAIN-JONES

Dr. Donald Thomas Germain-Jones died as the result of a boating accident in the River Thames, England on January 20th, 1960. He was only 54 years of age and had but recently retired from the post of Chief Geophysicist to the British Petroleum Co. Ltd. The untimely passing of so vigorous and likeable a character came as a great shock to his relatives, friends and late colleagues.

"D.T." was born on November 24, 1906, and received his early education at Dover High School in Kent and later at the Royal College of Science, London, where he received a First Class Associateship and a First Class Honours B.Sc. degree in 1926. A year later he was awarded the Diploma of the Imperial College and still later the Ph.D. degree for work in geophysics. He was a Fellow of the Institute of Physics, of the Royal Astronomical Society and of the Institute of Petroleum. He was also one of the early members (No. 257) of the Society of Exploration Geophysicists.

"D.T." began his long and distinguished career in exploration geophysics in 1927 when he joined the old Anglo-Persian Oil Co. Ltd. (now British Petroleum

Co. Ltd.) specializing in the seismic method, although for some years he worked on petroleum engineering problems. He was the first to realize by practical demonstration in the Iranian oilfields that the producing Asmari limestone, although possessing high velocity contrast, was a poor transmitter of diffracted energy on account of the unfavorable wave length/thickness factor, and that the strong first events recorded emanated from the deeper and much thicker Cretaceous limestone. He devised a matching profile method in the analysis of in-line refraction profiles long before the first paper on this subject appeared in GEOPHYSICS. By the refraction arc method, he discovered one of the biggest oilfields in S. W. Iran, at Lali.

During the war years he led a field party in an intensive search for oil fields in England and at the same time became an intelligence officer in the Home Guard. After the war, he continued seismic exploration both in Iran and in India, but returned to England in 1949 to organize British Petroleum's first geophysical research station at Kirklington Hall in Nottinghamshire.

His flair for orderliness (he was continually tying a knot in his handkerchief to remaind him of something he had to do) and research were incentive to the highly successful growth of this station to which many American and European geophysicists were invited. For several years he contributed articles to the Journal of the Institute of Petroleum on developments in exploration geophysics.

"D.T." was one of the founders of the European Association of Exploration Geophysicists and contributed greatly to the successful launching of Geophysical Prospecting in 1953. In 1954, he became its second president.

In 1953, he was posted as Chief Geophysicist to British Petroleum Co. Ltd., where his organizing qualities at a time of great exploration expansion were outstanding.

In his early days "D.T." was a strong long distance swimmer and a good walker, although both he and the writer were extremely uncomfortable after walking 32 miles in 8 hours on one occasion. In later years, he encouraged at Kirklington Hall, the formation of sports clubs, particularly in archery and rifle-shooting.

Dr. Germain-Jones is survived by his widow, mother, one daughter, a sister, Mrs. C. F. Dollin and a brother, Peter.

T. C. RICHARDS

CONTRIBUTORS

T. H. BRAUN was born in Germany in 1918 and came to California in 1926. He joined The Superior Oil Company geophysical laboratory in 1937, spent 4 years in New Zealand on a seismic crew, returned in 1943, and was appointed Director of Geophysical Research in 1951. In 1959 he became chief geophysicist of the Western Division of The Superior Oil Company.

Mr. Braun is a member of the Society of Exploration Geophysicists, the Institute of Radio Engineers, and the European Association of Exploration Geophysicists. He is a registered professional engineer (electrical) in the state of California. For the 29th International Meeting of the S.E.G., held in Los Angeles, he served as Technical Program Chairman.

In April, 1960, Mr. Braun resigned from The Superior Oil Company to accept a position with System Development Corporation, in Santa Monica, California.

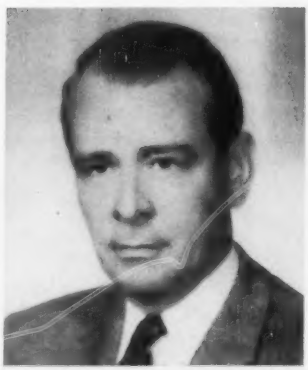
T. H. BRAUN

R. A. BRODING

R. A. BRODING received his B.S. degree in electrical engineering from the University of Minnesota in 1939. After serving in the geophysical department of Magnolia Petroleum Company as an electrical engineer, he worked from 1942 to 1943 on magnetic firing devices as a member of the Naval Ordnance Laboratory. From 1943 to 1953 he continued work for Magnolia on various seismic and electrical prospecting methods as well as magnetic and acoustic well logging instrumentation, including the continuous velocity log. Since 1953 he has been Technical Vice-President of Century Geophysical Corporation.

HARVEY L. BRYANT

HARVEY L. BRYANT graduated from the University of Oklahoma in 1951 with a B.S. in Geological Engineering. After graduation he served in the U. S. Navy as Chief Engineer of the destroyer U.S.S. *Picking* DD-685. In 1955 he joined the Creole Petroleum Corporation of Venezuela where he has done special studies work in geology, geophysics and well logging. Currently Mr. Bryant is on a one-year assignment with Jersey Production Research in the well logging research group.



LOUIS G. CHOMBART

LOUIS G. CHOMBART graduated from Ecole Centrale des Art et Manufactures of Paris in 1934 with a degree in Mines and Metallurgy, equivalent to an M.S. degree in the United States. He first came to the States in October, 1937, to join the ranks of Schlumberger Well Surveying Corporation as a Field Development Engineer. He held various high ranking positions with that Company until he resigned his post as manager of its Kansas and Oklahoma-Texas Panhandle Division in 1950, to devote his entire efforts to consulting in formation evaluation problems. Between 1950 and 1955 he was successively associated with Dr. R. G. Hamilton of Tulsa and Amstutz and Yates, petroleum consulting engineers, of Wichita. During 1956 he served as a consultant on formation evaluation problems in France and Africa for the French Petroleum Institute in Paris. Since 1956 he has conducted his consulting activities principally from Wichita, Kansas. He has written several papers on well logging techniques and formation evaluation through well logs.

He holds active memberships in the Society of Exploration Geophysicists, the Society of Petroleum Engineers of the American Institute of Mining and Metallurgical Engineers, the American Association of Petroleum Geologists, the Association Francaise des Techniciens du Pétrole, the Tulsa Geological Society and the Kansas Geological Society. He is a charter member of the Society of Professional Well Log Analysts and was its first Editor. He is Chairman of the API Mid-Continent District Study Committee on Formation Evaluation.

H. G. DOLL holds a B.S. degree from the University of Lyon, France. He graduated from the Ecole Polytechnique of Paris in 1923 and did graduate work with the Ecole des Mines from 1924–1926. From 1926–1940 he was employed by Societe de Prospection Electrique in Paris, first as a research engineer, then as Managing Director.

In 1940 he became Director of Research of Schlumberger Well Surveying Corporation in Houston, Texas. He moved to Ridgefield, Connecticut in 1948 as head of the Schlumberger Research Center.

He has served as President of Electro-Mechanical Research, a Schlumberger affiliate, and is now Technical Advisor and Chairman of the Board of Schlumberger.

H. G. DOLL

J. L. DUMANOIR

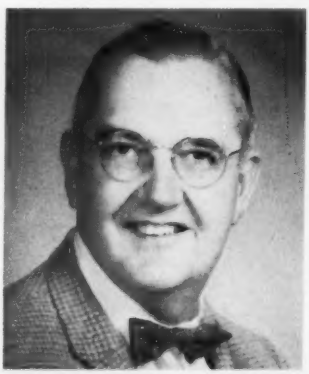
J. L. DUMANOIR took his B.S. degree from the University of Lille, France, and graduated from Ecole Polytechnique in 1942. He joined Schlumberger in 1946 as a field engineer in South America, and later was a district manager in Europe. In 1955 he moved to Ridgefield, Conn. as a research engineer in the Interpretations-Research Department of Schlumberger Well Surveying Corporation.

JOHN G. HEACOCK

JOHN G. HEACOCK graduated in 1942 with a B.S. in Physics from Franklin and Marshall College, Lancaster, Pennsylvania. During the war he worked at the SAM Laboratories of the Manhattan Project dealing with electronics and high vacuum techniques of mass spectrometer maintenance and research. From 1946–1948 he taught in the Department of Physics, Columbia University, as a graduate assistant, where he received an A.M. in 1950. During 1948–1949 he did field work with the Vening Meinesz pendulums, measuring gravity at sea aboard U. S. Navy submarines. From 1949–1953 he studied graduate geophysics and geology at the Lamont Geological Observatory, Columbia University.

Further experience includes the development of a D.C. current amplifier using saturable magnetic cores typical of aeromagnetometers and field work in seismology and underwater sound.

Mr. Heacock joined the Technical Services Division of Shell in 1954 as a geophysicist where he did applied research in gravity and magnetics and instructed in the geophysical training program. He is currently doing gravity interpretation and applied geophysical research with the New Orleans Area Exploration Department of Shell Oil Company.



HAMILTON M. JOHNSON

HAMILTON M. JOHNSON received his B.S. (physics and chemistry) and M.S. (physics and electrical engineering) degrees from the Louisiana State University in 1935 and 1936 respectively. He received the Ph.D. (geology and geophysics) from the University of Oklahoma in 1954 with a dissertation entitled "An Analysis of Subsurface Geophysical Methods in Determining Lithology and Fluid Content." After graduate work at Purdue University in physics, he was employed by Schlumberger Well Surveying Corporation as a well logging engineer and was in well logging management from 1937–1947, in Oklahoma, Texas, Louisiana, Wyoming, South Dakota, Mississippi, Arkansas, Tennessee, Kansas, and Venezuela.

He organized and managed a well logging subsidiary company for the Seismograph Service Corporation in Venezuela for several years; following sale of this subsidiary, he served as a logging consultant in Mexico and as a seismic computer in Colorado for this company, while taking graduate studies at the University of Oklahoma.

He returned to Venezuela in 1954 with the Texas Petroleum Company and served as District Geologist in the Las Mercedes area; then transferred to the Creole Petroleum Corporation as Well Logging co-ordinator for all of their operations. He is now Professor of Geology and Geophysics at Tulane University and also serves as a consultant on logging research with the Jersey Production Research Company.

He is a member of the Society of Exploration Geophysicists (program committee 1959), Society of Petroleum Engineers of AIME (program committee 1959), American Association of Petroleum

Geologists, Geological Society of America, American Geophysical Union, European Association of Exploration Geophysicists, Southeastern Geophysical Society, Seismological Society of America, The Sigma Xi, Sigma Gamma Epsilon, and Sigma Pi Sigma.

He is the author of some two dozen technical papers dealing with well logging techniques and interpretation.

EDWIN S. MARDOCK

EDWIN S. MARDOCK is a graduate of Stanford University where he received an A.B. degree in chemistry. His interest in the earth sciences and petroleum exploitation technology were acquired later during 23 years experience with a major oil company and a service company, respectively.

During his 11 years of oil company service, he was employed first in their research laboratories on problems related to well logging, secondary recovery, core analysis, and well treatment; later was transferred to the field where he was employed as an exploitation engineer. During a portion of this time he was responsible for his company's well logging program for a large geographical area.

The ensuing 12 years were spent in the employ of a service organization engaged in the development of well logging methods and equipment. He was responsible for the development of interpretation techniques for well logs as well as the field testing of new equipment and the analysis of the test data.

Recently he has become engaged in engineering consultation work within the fields of well logging and secondary recovery.

M. MARTIN

MAURICE MARTIN, General Manager of Geopetrole, Paris, France, holds a B.S. degree from the University of Paris, and graduated from Ecole Polytechnique of Paris in 1929. He joined Schlumberger in 1929 as a field engineer and advanced to the position of Manager of Operations in Europe. In 1948, he became affiliated with the Ridgefield Research Center of Schlumberger, as Head of the Publications-Interpretation Department. In January, 1960, he assumed his present position with Geopetrole.

J. J. PICKELL

J. J. PICKELL graduated from the University of California, Berkeley, in 1948, with a B.S. Degree in Civil Engineering. He joined Shell Oil Company as an Exploitation Engineer in 1948, and has since worked at various assignments for that company. His experience has been predominantly in the field of petrophysics in the Pacific Coast and Rocky Mountain Areas. Mr. Pickell is now assigned to the Exploration and Production Research Division of Shell Development Company, Houston, Texas.

JOSEPH L. POOLE received his B.S. degree in electrical engineering from the University of Alberta in 1946. He spent two years working with The Canadian Signals Research and Development Establishment in Ottawa. Poole joined Century Geophysical Corporation in 1949. His present position is that of Supervisor with Century Geophysical Corporation of Canada.

JOSEPH L. POOLE

G. Y. WHEATLEY attended Glendale J. C. and U.C.L.A. where he received a B.A. degree in 1936. Upon graduation he was employed by the Associated Oil Company, Ventura, California. From 1937 to the present he has been employed by The Superior Oil Company.

DR. M. R. J. WYLLIE, a South African, is Director of the Reservoir Mechanics Division of Gulf Research & Development Company at Harmarville, Pennsylvania. He was educated at the South African College School and the University of Cape Town (B.Sc. 1939). From Cape Town he went as a Rhodes Scholar to Oxford and proceeded to a D.Phil. degree in 1942; his thesis was on the structure of electrodeposited chromium. From 1942 to 1946 he served in the Royal and South African Navies in Europe and South East Asia working on the development of various secret weapons. In the academic year 1946–47 he was a post-doctoral fellow in the Department of Chemistry of The Johns Hopkins University. He joined Gulf in 1947.

Dr. Wyllie is the author of more than 50 technical papers and books. In 1958 he was given a D.Sc. degree by Oxford University.

M. R. J. WYLLIE

SOCIETY ROUND TABLE

COMMITTEES FOR THE YEAR ENDING IN NOVEMBER 1960

EXECUTIVE COMMITTEE

President: T. O. HALL, General Geophysical Company, Houston, Texas
First Vice-President: FRANK SEARCY, Continental Oil Company, Ponca City, Oklahoma
Vice-President: DEAN WALLING, Western Geophysical Co. of America, Los Angeles, California
Secretary-Treasurer: PHIL P. GABY, Consultant, Jackson, Mississippi
Editor: NELSON C. STEENLAND, Gravity Meter Exploration Company, Houston 27, Texas
Past President: E. V. MCCOLLUM, E. V. McCollum & Company, Tulsa, Oklahoma

Nominations
T. O. HALL, *Chairman*
E. V. MCCOLLUM
O. C. CLIFFORD, JR.

Tellers
JAMES F. JOHNSON, *Chairman*

Honors and Awards
ROY L. LAY ('60), *Chairman*
PAUL L. LYONS ('61)
R. C. DUNLAP, JR. ('62)
ROY F. BENNETT ('63)
O. C. CLIFFORD, JR. ('64)

SEG Foundation
H. M. THRALLS ('60), *Chairman of Trustees*
BART W. SORGE ('61), *Trustee*
RICHARD BREWER ('62), *Trustee*

Constitution and Bylaws
CURTIS H. JOHNSON, *Chairman*
W. W. HARDY
PAUL L. LYONS
L. L. NETTLETON
RAYMOND A. PETERSON

Scholarship Administration
ROBERT C. KENDALL, *Chairman*

AAAS Council Representative
CHARLES W. OLIPHANT

Distinguished Lectures
J. W. THOMAS ('60), *Chairman*
A. J. HINTZE ('60)
A. W. MUSGRAVE ('61)
CHARLES B. OFFICER ('62)
T. C. RICHARDS ('62)
GEORGE P. WOOLLARD ('61)

Safety
KENNETH A. WEBB, *Chairman*
R. N. BRANTLEY
E. L. WELLS
HERBERT FERBER
G. M. HINTZ
DON V. BIGELOW
CARL GERDES
JOHN RICHARDS
C. C. SELLERS, JR.

Mining Geophysics
STANLEY H. WARD, *Chairman*
ROBERT BOWMAN
KENNETH L. COOK
PHILLIP G. HALLOF
DON R. MABEY
D. J. SALT
JOHN SUMNER
H. LEROY SCHARON, *Chairman*
NELSON C. STEENLAND
ROBERT G. VAN NOSTRAND

Membership
JACKSON YOUNG, *Chairman*
AART DEJONG
MAYNARD W. HARDING
TOM KING
SAM TEASLEY
ROBERT L. TUCKER

Publicity
(To be appointed)

Business & Finance
FRANK BROWN ('60), *Chairman*
EDWARD H. WELTSCH ('61)

Publications
RICHARD A. GEYER, *Chairman*
W. M. RUST, JR.
MARK K. SMITH, JR.
J. A. PEOPLES

Subcommittee on Translation of Russian Publications
IRWIN ROMAN, *Chairman*
PAUL P. REICHERTZ
J. J. ROARK

Reviews
CARL H. SAVIT, *Chairman*
JAMES AFFLECK
W. L. BASHAM
F. G. BLAKE
PIERRIE L. GOUPILLAUD
ROLAND G. HENDERSON
NORMAN H. RICKER
JOSHUA L. SOSKE
S. H. WARD
ISIDORE ZIETZ

Index of Wells
V. U. GAITHER, *Chairman*

Case Histories
D. P. CARLTON, *Chairman*

Geophysical Activity
H. G. PATRICK, *Chairman*
K. L. COOK
R. J. COPELAND
HERBERT HOOVER, JR.
SANTOS FIGUEROA HUERTA
C. N. HURRY
DR. KUMIJI IIDA
BART W. SORGE
L. R. TUCKER

Radio Facilities
DR. S. KAUFMAN, *Chairman*
JOSEPH DELERNO, JR.
GLENN HARRIS
W. A. MCGARRY
DEAN MILLER
J. O. PARR, JR.
ROBERT RADEBAUGH
DAVID G. SCHWEITZER
LORENZ SHOCK
DANIEL SILVERMAN
MATTHEW SLAVIN
EDWIN L. TOMLIN
JAMES E. WALKER

Research
J. P. WOODS, *Chairman*
F. G. BLAKE, JR.
F. G. BOUCHER
C. H. FAY
JOHN C. HOLLISTER
JAMES F. JOHNSON
THEODORE R. MADDEN
A. L. PARRACK
FRANK PRESS
R. R. THOMPSON

Saftey
KENNETH A. WEBB, *Chairman*
DON V. BIGELOW
R. N. BRANTLEY
E. L. WELLS
HERBERT FERBER
CARL GERDES
G. M. KINTZ
JOHN RICHARDS
C. C. SELLERS, JR.

Delegates to I.U.G.G.
JACK OLIVER ('60)
W. A. HEISKANEN ('60)

LOCAL SECTIONS

Ark-La-Tex Geophysical Society (6), Shreveport, La., chartered March 12, 1949, officers elected in May. *Meetings:* Monthly, last Monday, noon luncheon ($1.50), Captain Shreve Hotel.
Virgil Teufel, *pres.*
J. A. Boydstun, *v-pres.*
R. H. Wardell, *secty-treas.*, Western Geophysical Co., 322 Fairfield Bldg., Shreveport, La.

Canadian Society of Exploration Geophysicists (9), Calgary, Alta., chartered January 24, 1952, officers elected in February. *Meetings:* Monthly, no set schedule.
Dr. M. B. Dobrin, *pres.*
P. J. Savage, *vice-pres.*
J. J. Hamilton, *secty.*, Canadian Society of Exploration Geoph., Shell Oil Co. of Canada, Ltd. P.O. Box 880, Calgary, Alta., Canada.
J. G. Goodwin, *treas.*

Casper Geophysical Society (11), Casper, Wyoming. Chartered May 23, 1953, officers elected in May. *Meetings:* Monthly, 1st Monday, 7:00 P.M., dinner ($2.75), Townsend Hotel, Casper, Wyoming.
G. L. Ellis, *pres.*
B. A. Tuller, *v-pres.*
Robert Davenport, *secty-treas.*, Wyoming Seismograph Co., Box 631, Casper, Wyoming.

Coastal Bend Geophysical Society (24), Corpus Christi, Texas, chartered May 29, 1959, officers elected in May.
Walter Pfennig, *pres.*
J. W. Bolinger, *v-pres.*
James Vetters, *treas.*
B. C. Johnson, *secty.* Forest Oil Corp., Box 1356, Corpus Christi, Texas.

Cochabamba Geophysical Society (23), Cochabamba, Bolivia, chartered May 4, 1959, officers elected in December.
R. H. Matthews, *pres.*
Charles W. Hyatt, *v-pres.*
Noel C. Manning, *secty.-treas.*, Geophysical Service Inc., Casilla #1437, Cochabamba, Bolivia.

Dallas Geophysical Society (4), Dallas, Texas, chartered August 7, 1948, officers elected in December. *Meetings:* Monthly, usually 2nd Monday, 8:00 P.M., Fondren Science Bldg., Southern Methodist University.
H. F. Dunlap, *pres.*
E. F. McMullin, *1st v-pres.*
M. S. Hathaway, *2nd v-pres.*
W. B. Heroy, Jr., *secty-treas.*, Geotechnical Corp., Box 28277, Dallas 28, Texas.

Denver Geophysical Society (8)
Meetings: Monthly, 1st Monday, 5:30 P.M., dinner at 7:00 P.M. ($3.00), Petroleum Club, Denver.
John C. Hollister, *pres.*
Arthur W. Black, *v.-pres.*
Charles E. McMunn, *secty-treas.* Tower Exploration Inc., P.O. Box 156, Englewood, Colorado.

Geophysical Society of Edmonton (22), Edmonton, Alta., Canada, chartered March 20, 1959, officers elected in December.
A. S. Gibson, *pres.*
R. F. Keller, *v-pres.*
R. D. Jacques, *secty-treas.*, Mobil Oil of Canada, Ltd., Financial Bldg., Edmonton, Alta.

Fort Worth Geophysical Society (5)
O. A. Strange, *pres.*
R. H. Dana, *v.-pres.*
U. A. Rowe, *secty.*
C. H. Thurber, *treas.*, Champlin Oil and Refining Co., Box 9365, Forth Worth, Texas.

Four Corners Geophysical Society (19), Durango, Colo., and Farmington, N. M., chartered June 19, 1958, officers elected in May.
J. P. Badami, *pres.*
F. E. Endacott, Jr., *1st v-pres.*
J. F. Wright, *2nd v-pres.*
G. D. Sindorf, *treas.*
L. E. Schneider, *secty.*, Empire Geophysical, Inc., Box 1484, Durango, Colo.

Geophysical Society of Houston (2), Houston, Texas, chartered February 14, 1948, officers elected in May. *Meetings:* Monthly, noon luncheon.
D. P. Carlton, *pres.*
S. P. Worden, *1st v-pres.*
K. A. Webb, *2nd v-pres.*
S. M. Pena, *treas.*
J. L. Bible, *secty.*, 1045 Esperson Bldg., Houston 2, Texas.

Jackson Geophysical Society (15)
Joel Macgregor, *pres.*
John Babb, *v-pres.*
Thomas Tillman, *secty.-treas.*, Sur. Oil Co., P.O. Box 850, Jackson, Miss.

Montana Geophysical Society (14), Billings, Mont., chartered April 12, 1954, officers elected in December. *Meetings:* Monthly, 2nd Monday, 7:30 P.M., Billings Petroleum Club.
W. H. Dawson, *pres.*
Phil Hendrick, *1st v-pres.*
F. J. Felice, *2nd v-pres.*
Max Judy, *secty.-treas.*, Sun Oil Co., Box 1896, Billings, Mont.

New Mexico Geophysical Society (18), Roswell, N. M., chartered September 18, 1957, officers elected in May.
R. E. Lawson, *pres.*
Delmer M. Woods, *1st v-pres.*
T. E. Daly, *2nd v-pres.*
R. W. Aldrich, *secty.-treas.*, Mobil Oil Co., 714 Petroleum Bldg., Roswell, N.M.

Geophysical Society of Oklahoma City (10), Okla. City, Okla., chartered September 30, 1952, officers elected in May. *Meetings:* Monthly, 2nd or 3rd Monday.
A. J. Oden, *pres.*
C. L. Howell, *1st v-pres.*
H. J. Fenton, *2nd v-pres.*
W. S. Hart, *treas.*
E. M. Peacock, *secty.*, Sohio Petroleum Co., 1606 N. Broadway, Oklahoma City, Okla.

Pacific Coast Section (3), luncheon ($2.75) Rodger Young Auditorium, Los Angeles.
F. F. Lambrecht, *pres.*
Nolan A. Webb, *v-pres. S.D.*
Fred G. Knight, *v-pres. N. D.*
Tom Slaven, *secty.-treas.*, Western Geophysical Co. of America, 523 W. 6th St., Los Angeles, Calif.

Permian Basin Geophysical Society (7), Midland, Texas, Chartered January 30, 1950, officers elected in December. *Meetings:* Monthly, 2nd Tuesday, 7:30 P.M., Midland Women's Club.
J. E. Clark, *pres.*
E. E. Fickenger, *1st v-pres.*
B. H. Hinton, *2nd v-pres.*
S. T. Miller, *treas.*
L. M. Scofield, *secty.*, Burton Exploration Co. Inc., 4513 W. Storey, Midland, Texas.

Regina Geophysical Society (22)
A. C. Armstrong, *pres.*
M. MacIver, *v-pres.*
J. R. Muir, *secty.-treas.*, The California Standard Co., 1836 Smith St., Regina, Saskatchewan, Canada.

Geophysical Society of South Texas
J. W. E. Edmonson, *pres.*
P. J. Rudolph, *v-pres.*
Donald W. Jones, *secty.-treas.*, Sun Oil Co., 832 Milam Bldg., San Antonio, Texas.

Southeastern Geophysical Society (13), New Orleans, La., chartered April 1, 1954, officers elected in January. *Meetings:* Monthly, 3rd Monday, noon luncheon ($2.00), Monteleone Hotel.
George Morgan, *pres.*
J. T. McMaster, *1st v-pres.*
D. R. Scheel, *2nd v-pres.*
O. J. Rauschenbach, *secty.-treas.*, Continental Oil Co., 414 Carondelet Bldg., New Orleans 12, La.

Southwest Louisiana Geophysical Society (16), Lafayette, La., chartered January 4, 1956, officers elected in December.
Jack Wallner, *pres.*
Walter Hurt, *1st v-pres.*
Richard Hollenbaugh, *2nd v-pres.*
Ned Pratt, *treas.*
Lucius Geer, *secty.*, Union Oil of California, Box 1224 OCS, Lafayette, La.

Geophysical Society of Tulsa (1)
Tulsa, Okla., chartered February 2, 1948, officers elected in May.
T. S. Green, *pres.*
J. E. Hawkins, *1st v-pres.*
K. S. Cressman, *2nd v-pres.*
B. L. Bass, *secty.*, Geophysical Society of Tulsa, Texaco, Inc., P.O. Box 2420, Tulsa, Okla.
Robert B. Fisher, *treas.*

Utah Geophysical Society (17)
L. D. Oster, *pres.*
K. L. Cook, *1st v-pres.*
H. H. Nuttli, *2nd v-pres.*
D. J. O'Halloran, *secty.-treas.*, Standard Oil of California, P.O. Box 1076, Salt Lake City Utah.

Asociacion Venezolana de Geofisica (20), Caracas, Venezuela, chartered January 5, 1959, officers elected in March.
E. J. Assiter, *pres.*
D. W. Danz, *1st v-pres.*
Gunther Fiedler, *2nd v-pres.*
Manuel Zegarra, *secty.*, Asociacion Venezolana de Geofisica, Phillips Petroleum Co., Apartado 1031, Caracas, Venezuela.
C. O. Hill, *treas.*

STUDENT SOCIETIES AFFILIATED

Colorado School of Mines Society of Student Geophysicists
Joseph R. Anzman, *secty.* Department of Geophysics, Colorado School of Mines, Golden, Colorado.
Meetings: Monthly, 2nd Monday, 4:00 P.M.

Geophysical Society of Saint Louis University
Norman J. Guinzy, *secty.* 410 Vandalia, Collinsville, Illinois.
Meetings: Monthly, 2nd Wednesday 7:30 P.M., meeting only, Institute of Technology.

SEG Houston Student Section
Billie Gail Dopslauf, *secty.* 2121 Hollister, Houston, Texas

University of Toronto Geophysical Society
B. R. Krause, *secty.* 502 Gilbert Ave., Apt. 107, Toronto, Ont., Canada

University of Tulsa Student Geophysical Society
Fred D. Munzlinger, *secty.* Department of Geophysics, 600 South College, Tulsa, Oklahoma.
Meetings: Weekly, Thursday, 4:00 P.M., Petroleum Science Bldg.

Trans-Pecos Student Section
El Paso, Texas

Pennsylvania State University Geophysical Society
Wm. R. England, *secty.* College of Mineral Industries, University Park, Pa.
Meetings: to be announced.

University of Utah Geophysical Society
James D. Morgan, *secty.* College of Mines and Mineral Industries, Salt Lake City 1, Utah.
Meetings: Monthly, 1st Thursday Noon, Mines Building. Other special meetings to be announced.

A & M College of Texas Student Geophysical Society
Edward C. Hanson III, *secty.* Geology and geophysics dept., A & M College of Texas, College Station, Texas.

SOCIETY AFFILIATIONS

American Association for the Advancement of Science

SEG is affiliated under Section E, Geology and Geography
1515 Massachusetts Avenue
Washington 5, D. C.
Paul E. Klopsteg, *President*
Paul A. Scherer, *Treasurer*
Dael Wolfle, *Executive Officer*

The American Association of Petroleum Geologists

A Cooperative relationship
Box 979
Tulsa 1, Oklahoma
L. G. Weeks, *President*
A. H. Bell, *Vice-President*
H. T. Morley, *Secretary-Treasurer*
G. E. Murray, *Editor*
G. S. Buchanan, *Past President*
R. H. Dott, *Executive Director*

European Association of Exploration Geophysicists

Mutually affiliated
30, Carel Van Bylandtlaan
The Hague, Netherlands
J. M. Bruckshaw, *President*
V. Baranov, *Vice-President*
B. Baars, *Secretary-Treasurer*
O. Koefoed, *Editor*
L. Solaini, *Past President*

National Research Council, Division of Earth Sciences

SEG is a member society
2101 Constitution Ave., N.W.
Washington 25, D. C.
John N. Adkins, *Chairman*
Harry H. Hess, *Past Chairman*
Edward B. Espenshade, Jr., *Chairman-Designate*
William R. Thurston, *Executive Secretary*

Petroleum Exploration Society of Libya

Mutually Affiliated
P. O. Box 900
Tripoli, Libya
R. E. Doan, *President*
P. F. Burollet, *1st Vice-President*
J. F. Rominger, *2nd Vice-President*
J. C. Wilson, *Secretary*
P. Arni, *Treasurer*
J. S. Cullison, *Director*
R. S. M. Templeton, *Director*

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the names of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

Byron R. Anderson (C. W. Kerns, Quin Hayes, O. H. Armstrong)
Billy G. Baugh (J. W. Hammond, W. O. Heap, C. C. Perry, Jr., J. G. Jackson)
Lloyd W. Berkner
Richard V. Brown (K. M. Lawrence, A. I. Innes, J. S. Hopkins)
Livin Constantinescu
Ken Graybill (J. E. Hughes, G. A. Howard, C. M. Moore, N. A. van der Schroof)
Thomas J. Hitchcock (J. A. Hafer, A. H. McKee, W. Blair, W. H. Dow)
Henry M. Hobart, Jr. (David Reed, L. W. Hoar, Joe Marucheck, C. W. Oliphant)
Arthur G. Lange (A. C. Armstrong, R. H. Carlyle, R. A. Boulware, R. J. Copeland)
Foy Lee Otts (W. M. Anderson, E. I. Barton, M. H. Lea, C. G. MacBurney)
Geo. E. Peetz (Vernon Boysen, R. D. Wyckoff, L. D. Palmer, Charles Frobese)
Wm. W. Weigel

APPLICATION FOR TRANSFER TO ACTIVE MEMBERSHIP

Robert E. Bearnth (Willard T. Nutt, C. K. Fielder, C. P. Montgomery)
Clovis O. J. Britton (W. W. Adams, C. C. Sellers, E. M. Peacock, C. C. Lilley)
Clarence I. Klipfel (J. J. Robnett, F. A. Grimm, A. A. Moore, Jr., C. H. Moore)
Leonard Rosenfeld
Sheridan W. Tift
D. M. Vander Stoep
Robert B. Wall
William W. Welch
Windle F. Wilhite

ANNOUNCEMENTS

DR. MAURICE EWING RECEIVES VETLESEN PRIZE

Dr. Maurice Ewing, recipient of the first Vetlesen Prize for outstanding achievement in the earth sciences, got his start in the oil business. His first job upon graduation from The Rice Institute in 1926 was torsion balance interpreter on a geophysical crew for the Humphries Corp., Houston, Texas. He returned to Rice for graduate work, and during the following summers worked on seismic field crews for Geophysical Research Corp. and received his Ph.D. in physics in 1929. His thesis was titled "Calculation of Ray Paths from Seismic Time Curves," a geophysical exploration problem.

Ewing became acquainted with many of the pioneers in geophysical prospecting while working in the oil fields of Texas and Oklahoma. Among the many congratulatory messages Ewing has received from world-renowned scientists is a letter from T. O. Hall, president of the Society of Exploration Geophysicists, who said "This award is only a demonstration to the world at large of what the geophysicists have known for many years, that you are not only one of the world's outstanding geophysicists, but also one of the world's outstanding men in the earth sciences. The Society of Exploration Geophysicists is especially proud that one of its members has been awarded the first Vetlesen Prize." Ewing is an Honorary Member of SEG.

The prize, which consists of a gold medal, $25,000 and support of publication of the recipient's scientific papers, was presented at a dinner in Columbia University's Low Memorial Library, March 24. Leading scientists from all over the world were present, and the principal address was given by Dr. Alan T. Waterman, director of the National Science Foundation, Washington, D. C.

PHILLIPS PETROLEUM COMPANY RECEIVES DEVELOPMENT AWARD

The Phillips Petroleum Company was selected to receive the first annual Industrial Professional Development Award of the National Society of Professional Engineers.

The Award, and engraved plaque, was presented at the annual meeting of the 52,000-member engineering group in Boston, June 8–11.

A 5 member National Society Industrial Award Committee selected Phillips because of its "outstanding advancement and improvement in the development and application of forward-looking engineering employment practices."

Phillips Petroleum was selected for the Award from nominations of industrial firms throughout the U. S. by local chapters of the National Society. The Award will be presented by the National Society president each year in June at the group's annual meeting.

ENGINEERS JOINT COUNCIL ANNOUNCES NEW PUBLICATION

A new mass circulation newspaper for engineers entitled "Engineer" has been launched by Engineers Joint Council, a federation of 21 engineering societies, whose membership totals 300,000.

"The greatly increasing role of the engineer in national affairs; the problems facing the individual engineer and the total profession; and the rapid-fire pace of technical developments demand a means of communication among all engineers—regardless of specialty," EJC President Augustus B. Kinzel said in announcing the new publication.

Financed by a small allocation from membership dues engineers pay to their societies, the Spring issue of the quarterly publication has been mailed to each individual member of the national societies within the continental United States.

The first issue digests and interprets national news of interest to engineers. It also has articles of long-range interest to the profession—such as the impending future shortage of engineers and the bright job outlook for engineering employees.

The next issue is scheduled for June. Controlled by a Board of Directors representing the entire Council membership, the publication is supervised by an Editorial Advisory Board.

SPACE SCIENCE BOARD REPORT STRESSES NEED FOR SCIENTIFIC EXPLORATION OF THE MOON AND PLANETS

Satellites and space probes may some day enable man to determine the origin and evolutionary history of the solar system. This compelling scientific reason for the study and exploration of the Moon and the planets is discussed in two sections published today as the first part of a technical report on "Science in Space" being prepared by the Space Science Board of the National Academy of Sciences.

The chapters issued today, entitled "The Moon" and "The Planets," were prepared for the Board by one of its members, Dr. Harold C. Urey, Nobel Prize-winner and Professor at Large of the University of California at La Jolla. Dr. Urey is Chairman of the Space Science Board's Committee on Chemistry of Space and Exploration of Moon and Planets.

The chapters on the Moon and the planets summarize current views on these space companions of the Earth; areas of uncertainty and controversy are noted, as well as facts which seems to be well established. The sections also contain suggestions for lunar and planetary studies worthy of major emphasis in the national space effort.

Dr. Urey reviews what we know of the Moon and the planets and concludes that information on their atmospheres, surfaces, interior structures, and magnetic fields, radioed to Earth from scientific instruments near or on these celestial bodies, may resolve many of the existing uncertainties concerning the last four and one-half billion years. It is even possible that these lunar and planetary studies will lead to one of the most fascinating discoveries of all modern science: Evidence of present (or extinct) life on these planets. This possibility is only one of many beckoning men into space on a quest to unravel the puzzles of the universe.

The purpose of the Space Science Board's report, "Science in Space," is largely two-fold: to review areas and opportunities for important research studies using space vehicles and to suggest what now appear to be major areas of emphasis for the national space effort. The report, written by leading scientists who are, in the main, members of the Board, outlines the potentials of space science for the immediate future with a view toward encouraging broad participation in space research at every level of American scientific activity.

The report will consist of nine chapters. In addition to the two issued today, other titles are: "Physics of Fields and Energetic Particles in Space"; "The Nature of Gravitation"; "The Earth"; "The Sun"; "The Biological Sciences and Space Research"; "Galactic and Extra-galactic Astronomy"; and "A General Review."

Each chapter will be available from the Printing and Publication Office of the National Academy of Sciences, 2101 Constitution Avenue, N. W., Washington 25, D. C., for $1.00.

DALLAS GEOLOGICAL-GEOPHYSICAL SOCIETY PHOTO DIRECTORY

The 1960 Photo Directory of the Dallas Geological and Geophysical Societies has been published and is currently being distributed to the 750 members of the two societies.

In addition to the membership photos, the directory contains a listing of the past and present officers, committees, a cross reference by company affiliation, roster of independents and the constitution and by-laws of each of the societies.

Copies of the directory can be obtained by non-members for $2.00 each. They are available from the Secretary, Dallas Geological Society, Box 253, SMU Station, Dallas.

Other society publications available include the Geological Highway Map of Texas for $1.00 and the Cooke-Grayson County and Ouachita Symposiums for $10.00 each.

PROFESSIONAL WELL LOG ANALYSTS HOLD FIRST ANNUAL MEETING

The Society of Professional Well Log Analysts held their First Annual Meeting and Logging Symposium in Tulsa on May 15–17.

The Symposium contained the following papers:

"Introductory Remarks," Wm. B. Belknap, Phillips Petroleum Co., Bartlesville, Okla.

"Log Analysts Are Important People," M. W. Haas, Humble Oil & Refining Co., Tulsa, Okla.

"A Review of Fundamental Nuclear Physics Applied to Well Logging," Joe D. Owen, Phillips Petroleum Co., Bartlesville, Okla.

"Exploration for Petroleum Traps Using Rocky Mountain Electric Log Evaluation," Bob Jones, Consultant, Casper, Wyoming

"Use of Flowing Well Logs in Solving Production Problems," Harvey L. Bryant, Jersey Production Research Co., Tulsa, Okla.

"Accuracy of Porosity Determination," Ralph E. Jenkins, Core Laboratories, Inc., Dallas, Texas

"Application of the Proximity Log," Robert G. Hamilton, Consultant, Tulsa, Oklahoma

"A Method of Off-Location Quantitative Mud Analysis for Hydrocarbons," Wendell H. Russell, Baroid Div. Nat'l. Lead Co., Houston

"A Method for Determining Formation Permeability from Well Logs," Jarl P. Johnson, Kewanee Oil Co., Odessa, Texas

"Some Petrophysical Aspects of the Mississippian Chat, Glick Pool, Kiowa County, Kansas," Jack D. Duren, Shell Oil Co., Roswell, New Mexico

"Resistivity-Velocity Log Evaluation of the Morrow Sand in Western Oklahoma," F. S. Millard, Humble Oil & Refining Co., Tulsa, Oklahoma

"Field Results with Nuclear Magnetism Logging," Paul W. Hull, Standard Oil Co. of Texas, Houston, Texas; John E. Coolidge, Byron Jackson Div. of Borg Warner Corp., Los Angeles, California

"Interpretation of Dipmeter Surveys in Mississippi," James A. Gilreath, Schlumberger Well Surveying Corp., Houston, Texas

The Society announced the election of William B. Belknap, of Phillips Petroleum Co., Bartlesville, as president, succeeding Frank S. Millard, Carter division of Humble Oil & Refining Co., Tulsa. First vice-president is J. Henry Blackburn, Sunray Mid-Continent Oil Co., Tulsa, and second vice-president, Ray L. Braeutigam, Sinclair Oil & Gas Co., also of Tulsa. L. Guy Huntley, Carter division of Humble, Oklahoma City, was elected secretary-treasurer, Anthony V. Messineo, Atlantic Refining Co., Dallas, editor, and members at large are R. G. Hamilton, consultant of Tulsa, and Paul W. Hull, Standard Oil Co. of Texas, Houston.

PERSONAL ITEMS

DR. P. K. BHATTACHARYA has recently been promoted to the rank of Professor of Geophysics and is in charge of the Geophysics Laboratory of the Department of Geology and Geophysics at the Indian Institute of Technology, Kharagpur, India. After twenty months of study and research at different geophysical research centers in the U.S.S.R. on an Unesco grant, he has recently returned to India to assume the charges of the laboratory.

DEBKUMAR GANGULI has recently been promoted to the rank of Assistant Professor of Geophysics in the Department of Geology and Geophysics of the Indian Institute of Technology.

DR. H. W. STRALEY III, Professor of Geology, will represent the Georgia State Department of Mines, Mining and Geology and the Georgia Institute of Technology at the International Geological and Geophysical Congresses at Copenhagen and Helsinki this summer. At Helsinki, Dr. Straley will present a paper, co-authored with Mr. John E. Husted, Head, Minerals Engineering Group of Tech's Engineering Experiment Station, on the "Relation of the Appalachian Earthquake Pattern to Blue Ridge, Virginia, Faulting."

JOE W. HAMMOND, staff supervisor of foreign operations for Seismograph Service Corporation, has been elected assistant vice-president of the company, it was announced today by G. H. Westby, president.

JAY H. SIMONS, former geologist with the New York Exploration Division of the Gulf Oil Corporation, is now Manager, Mineral Fuels Division, of Geotechnics and Resources Inc., White Plains, New York.

FRANK GOLDSTONE, consultant, has recently entered into a partnership with Geoprosco of London. His new address is: Geoprosco, 20 Albert Embankment, London, S.E. 11, England.

T. H. BRAUN formerly with The Superior Oil Company is now employed by the System Development Corporation, 2500 Colorado Avenue, Santa Monica, California.

"With the amalgamation on January 1st of Hunting Technical & Exploration Services Limited with Hunting Airborne Geophysics Limited and The Photographic Survey Corporation Limited into Hunting Survey Corporation Limited, DR. NORMAN PATERSON, formerly Chief Geophysicist of Hunting Technical & Exploration Services Limited, becomes Chief Geophysicist of Hunting Survey Corporation Limited. In this capacity Dr. Paterson assumes responsibility for the technical direction of all airborne, ground and marine geophysical activities of the company.

MR. D. G. MACKAY, formerly General Manager of Hunting Airborne Geophysics Limited has been appointed General Manager of Hunting Survey Corporation Limited.

S. A. HATCHER, formerly District Geophysicist in New Orleans, is now Area Geophysicist in charge of all geophysical interpretation in the Gulf Coast Area, for the Sohio Petroleum Company.

E. H. URQUHART has been named a Staff Sales Engineer for Texas Instruments Incorporated Geosciences & Instrumentation division's Instrumentation product group, O. F. Henning, Marketing Manager, announces.

Acquisition of Midland Geophysical Company, Midland, Texas, facilities and personnel by Empire Geophysical, Inc., of Fort Worth, Texas, has been announced by HOWARD ITTEN, Empire president. The acquisition is effective May 1, 1960. Empire is a Sustaining Member of SEG.

Mr. Itten also announced the appointment of LORENZ SHOCK, who founded Midland Geophysical, as Empire vice-president and chief geophysicist.

Mr. Shock, a 1937 graduate of the University of Oklahoma, organized Midland Geophysical in 1951.

The formation of a new department for marine operations and several key appointments in Geophysical Service Inc. have been announced by R. C. DUNLAP, JR., president of the Dallas-based geophysical exploration firm.

The marine operations, which will headquarter in London, England, will be primarily concerned with GSI's single-ship marine seismic exploration, including the 400-ton motor vessels *Sonic* and *Texin*.

Heading the marine operations is PAUL V. HODGE. Mr. Hodge has been with GSI since 1945 and has held various positions in land and marine seismic exploration. He was in charge of the SONIC when it first began operations in 1954 and, in his former position as Equipment Manager, was most recently charged with the outfitting of GSI's new seismic exploration vessel, the TEXIN.

Succeeding Hodge as Equipment Manager is JACK V. MCMANUS, a 24-year veteran with GSI. Mr. McManus, who had been GSI's Chief Field Service Engineer since 1955, will continue to maintain headquarters in Dallas.

Geophysical Exploration Company of Houston has announced that NEAL CLAYTON has joined the firm as a supervisor of field operations. Mr. Clayton will direct and coordinate crew operations throughout Texas and Louisiana from the Houston headquarters.

Mr. Clayton, whose experience in geophysical prospecting spans 23 years, has held assignments in all major oil producing areas of the United States with the Humble Oil & Refining Company, Magnolia Petroleum Co. and Sohio. Just prior to joining Geophysical Exploration, he served as District Geophysicist for Sohio in Lafayette.

He is a member of the American Association of Petroleum Geologists, the Lafayette Petroleum Club and is a past president of the Lafayette chapter of the Society of Exploration Geophysicists. Mr. Clayton is also the author of a number of papers on geophysical exploration which have appeared in several oil trade publications.

CALENDAR OF MEETINGS

1960

August

8–12 American Institute of Electrical Engineers, Pacific General Meeting, San Diego, California.
23–25 Association for Computing Machinery, National Meeting, Milwaukee, Wisc.

October

2–5 Society of Petroleum Engineers of AIME, Fall Meeting, Denver, Colorado.
12–14 Third Annual Meeting, Southwestern Federation of Geological Societies, Abilene, Texas.
19–21 Gulf Coast Association of Geological Societies, Biloxi, Mississippi.
31–Nov. 2 GSA Annual Meeting, Denver, Colorado.

November

3–4 Pacific Section AAPG, Los Angeles
7–10 Society of Exploration Geophysicists, 30th Annual International Meeting, Moody Convention Center, Galveston, Texas.
14–16 API, Chicago, Illinois.

1961

February

19–23 AIME Annual Meeting, St. Louis, Missouri.

March

20–23 IRE National Convention, New York City.

April

24–27 AAPG-SEPM Annual Meeting, Denver, Colorado.

October

8–11 Society of Petroleum Engineers of A.I.M.E., Annual Meeting, Dallas, Texas
18–21 AAPG Mid-Continent Regional Meeting, Amarillo, Texas.
25–27 Gulf Coast Association of Geological Societies, San Antonio, Texas.

November

2–4 GSA Annual Meeting, Cincinnati, Ohio.
5–9 Society of Exploration Geophysicists, 31st Annual International Meeting, Denver, Colorado.
9–10 Pacific Section AAPG, Los Angeles
13–15 API, Chicago, Illinois.

1962

March

26–29 AAPG-SEPM Annual Meeting, San Francisco, California.
26–29 IRE National Convention, New York City.

September

17–20 Society of Exploration Geophysicists, 32nd Annual International Meeting, Calgary, Alberta.
7–10 Society of Petroleum Engineers of A.I.M.E. Annual Meeting, Los Angeles, California.

Oct. 31–Nov. 3 Gulf Coast Ass'n of Geological Societies, New Orleans, La.

November

12–14 GSA Annual Meeting, Houston, Texas.

1963

March

25–28 AAPG-SEPM Annual Meeting, Houston, Texas.

October

6–9 Society of Petroleum Engineers of A.I.M.E. Annual Meeting, New Orleans, La.

24–28 Society of Exploration Geophysicists, 33rd Annual International Meeting, New Orleans, La.

November

13–16 Gulf Coast Ass'n of Geological Societies, Hot Springs, Ark.

PROFESSIONAL DIRECTORY

ARIZONA

HEINRICHS GEOEXPLORATION CO.
Mining Oil & Water Consultants & Contractors
Geophysics Geology & Geochemistry
Examination-Interpretation-Evaluation
MOBILE MAGNETOMETER SURVEYS
Walter E. Heinrichs, Jr.
P.O. Box 5671 Tucson, Ariz. Phone: MAin 2-4202

CALIFORNIA

H. WAYNE HOYLMAN
Consultant
Petroleum and Mining Exploration
Aerogeophysics Company 816 W. 5th St.
MAdison 8-6428 Los Angeles 17, Calif.

L. F. IVANHOE
Consulting Geologist and Geophysicist
Domestic and Foreign Exploration
Phone: FA 50283 2810 Elmwood Avenue
CABLE: IVANHOE BAKERSFIELD, CALIFORNIA

CURTIS H. JOHNSON
Geophysical Consultant
Domestic & Foreign
816 WEST 5TH STREET, LOS ANGELES 17, CALIFORNIA
Phone: MAdison 6-0020

WILLIAM CROWE KELLOGG
Geological Engineer
Kellogg Exploration Company
Geologists — Geophysicists
Electrical — Magnetic — Gravity — Radioactivity
Air-Ground Surveys Interpretation
3301 NORTH MARENGO ALTADENA, CALIFORNIA

HENRY SALVATORI
Western Geophysical Company
of America
1116 Pacific Mutual Bldg.
523 W. 6th Street
LOS ANGELES 14, CALIFORNIA

ARIZONA

JOSHUA L. SOSKE
Geologist and Geophysicist
Dept. of Geophysics
SCHOOL OF MINERAL SCIENCES
Stanford University
STANFORD, CALIFORNIA

CALIFORNIA

ELLIOTT SWEET
Gravity Meter Surveys
Gravity and Seismic Interpretation
SWEET GEOPHYSICAL CO.
21544 Rambla Vista Drive
MALIBU, CALIFORNIA

COLORADO

Milt Collum Wes Morgan
PETROLEUM GEOPHYSICAL COMPANY
Contract Seismograph Crews
Seismic Review and Interpretations
Rocky Mountain Area
KEystone 4-0253
2011 Glenarm Denver 5, Colorado

LOUISIANA

MISSISSIPPI

EWIN D. GABY
Delta Exploration Company
Jackson Mississippi

MISSOURI

LEROY SCHARON
Mining and Engineering Geophysics
567 Brookhaven Court
Kirkwood 22 Phone
St. Louis, Missouri YOrktown 6-4245

NEW YORK

ROLAND F. BEERS
ROLAND F. BEERS, INC.
Petroleum and Minerals Exploration Consultants
Ground and Airborne Surveys
Data Reduction and Analysis
P.O. Box 1019 Troy, New York
ASbley 2-6478; 2-2351

OKLAHOMA

THOMAS J. BEVAN
Geophysicist
914 American Airlines Bldg. Phone CHerry 2-7508
TULSA 3, OKLAHOMA

ARNOLD H. BLEYBERG
Petroleum Exploration Consultant
Domestic & Foreign Services
MID-AMERICA BANK BLDG.
OKLAHOMA CITY 2, OKLA. PH.: CENTRAL 2-0913

CRAIG FERRIS
Geophysicist
E. V. McCollum & Co. GeoSeis, Inc.
Namco, International
515 Thompson Bldg.
TULSA 3, OKLA.

Contractor and Consultant — Research and Developments
V. L. JONES
TERRAMETRIC EXPLORATION COMPANY
GEOPHYSICAL AND GEOLOGICAL SERVICES
P.O. Box 3731 Phone
TULSA 23, OKLA. DI 3-0012

TOM D. MAYES
Mayes-Bevan Co.
Gravity Meter Surveys
and Interpretations
345 Kennedy Building
TULSA, OKLAHOMA

OKLAHOMA

E. V. McCOLLUM
Geophysicist
E. V. McCollum & Co. Geo Seis, Inc.
Namco, International
515 Thompson Building
TULSA, OKLAHOMA

GLENN M. McGUCKIN
Seismograph Consultant
Data Interpretation Current Supervision
SALES: McGUCKIN (Patented) SEISMOGRAPH
SECTION PLOTTER (DIP MIGRATOR)
25 Years Experience:
Supervising, Contracting, Consulting
Phone JEfferson 4-0853 1304 Ann Arbor
NORMAN, OKLA.

RICHARD A. POHLY
Gravity Surveys and Re-interpretation
POHLY EXPLORATION COMPANY
1135 E. 38th St. RIverside 2-2009
TULSA 5, OKLAHOMA

BEN F. RUMMERFIELD
Geologist and Geophysicist
CENTURY GEOPHYSICAL CORPORATION
503 Jenkins Building 1105 7th Ave., W.
Tulsa 3, Oklahoma Calgary, Alberta

JOHN J. RUPNIK
Petroleum Exploration Consultant
GEOPHYSICAL & GEOLOGICAL COORDINATION
J. J. RUPNIK AND COMPANY
730 BEACON BLDG., Telephone LU 4-6355
TULSA 3, OKLAHOMA

HUGH M. THRALLS
Consulting Geophysicist
Box 9577 GIbson 7-3921
TULSA, OKLAHOMA

TEXAS

JOHN F. ANDERSON
ANDERSON & COOKE
Oil Exploration Consultants
Geological Consulting
Seismic Surveys & Interpretations
665 San Jacinto Bldg. Houston 2, Texas

WALTER D. BAIRD
Consulting Geophysicist
NEIL P. ANDERSON BUILDING
PHONE EDison 6-8400 FORT WORTH 2, TEXAS

KEITH R. BEEMAN
Electronic Consultant
Seismograph and Allied Equipment
P.O. Box 13058
Houston, Texas

JOHN L. BIBLE
Gravity-Magnetic-Surveys-Interpretations
Bible Geophysical Co., Inc.
1045 Esperson Bldg. Houston 2, Texas

HART BROWN
Brown Geophysical Company
Gravity-Meter-Surveys
Interpretations
5300 Brownway Rd. Houston 19, Texas

R. A. CRAIN
Texas Seismograph Company
1502 Eighth St.
WICHITA FALLS, TEXAS

R. H. DANA
Dana Explorations, Inc.
1301 W. T. Waggoner Bldg.
Fort Worth, Texas

TEXAS

PAUL FARREN
Geophysical Consultant
Specializing in Seismic Interpretation,
Review, and Supervision
1528 Bank of the Southwest
HOUSTON 2, TEXAS FA 3-1356

L. F. FISCHER
Exploration Consultant
Geophysicist
Geologist
624 First City Bank Bldg. Houston 2, Texas

J. F. FREEL
RESEARCH EXPLORATIONS, INC.
5134 Westheimer Road
Houston, Texas

JOHN A. GILLIN
National Geophysical Company, Inc.
Namco International, Inc.
2345 West Mockingbird Lane
Dallas, Texas

T. I. HARKINS
Independent Exploration Company
1973 West Gray
P.O. Box 13237
Houston 19, Texas

J. G. HARRELL
Geophysicists
2810 Primrose St. Telephone
Fort Worth, Texas TE 8-0284

TEXAS

J. O. HOARD
HOARD EXPLORATION COMPANY
Esperson Building — Houston, Texas

W. B. HOGG
Geophysical Consultant
619 Fidelity Union Life Bldg.
DALLAS 1, TEXAS

JOHN S. IVY
Niels Esperson Building
HOUSTON, TEXAS

J. C. KARCHER
Geophysicist
Adolphus Tower
DALLAS, TEXAS

MARTIN C. KELSEY
Rayflex Exploration Company
6923 Snider Plaza — Dallas 5, Texas

H. KLAUS
Geologist and Geophysicist
Klaus Exploration Company
Gravimetric and Magnetic Surveys and Interpretations
P.O. Box 1617 — Lubbock, Texas

PAUL H. LEDYARD
Mid-Continent Geophysical Co.
Contract Seismograph Crews
Seismic-Reinterpretations
2509 West Berry — Fort Worth, Texas

TEXAS

C. T. MacALLISTER
Geophysical Consultant
Seismic Interpretations and Field Supervision
6327 Vanderbilt, Houston 5, Texas — Telephone: MA 3-4181

HAYDON W. McDONNOLD
Geologist & Geophysicist
Keystone Exploration Company
2813 Westheimer Road
HOUSTON, TEXAS

A. E. "SANDY" McKAY
Geologist and Geophysicist
Continental Geophysical Company
Namco International, Inc.
FORT WORTH, TEXAS
1409 Continental Life Bldg., Phone EDison 2-9231

GEORGE D. MITCHELL, JR.
Geologist and Geophysicist
911 Mercantile Securities Bldg. — Dallas, Texas

P. E. NARVARTE
Consulting Geophysicist
Seismic Interpretations
Current Supervision and Review
Frost National Bank Building
San Antonio, Texas

L. L. NETTLETON
Gravity Meter Exploration Co.
Interpretation of Gravity Surveys
Interpretation of Aeromagnetic Surveys
3621 W. Alabama
HOUSTON 27, TEXAS

W. W. (IKE) NEWTON
Geophysicist
823 Corrigan Tower
DALLAS, TEXAS

TEXAS

J. O. PARR, JR.
Consulting Geophysicist
Methods & Instrumentation
for
Seismic & Radiometric Surveys
202 Janis Rae San Antonio, Tex.

C. W. PAYNE
Exploration Consultant
Geology—Geophysics
812 Continental Life Bldg.
FORT WORTH TEXAS

H. B. PEACOCK
Consulting Geophysicist
9746 Audubon Place
DALLAS 20, TEXAS

J. C. POLLARD
GEOPHYSICAL ENGINEERING
•
SEISMIC . . . GEOGRAPH . . . GRAVITY
MAGNETIC SURVEYS
•
2500 Bolsover Rd., P.O. Box 6557, Houston 5, Tex.

ROBERT H. RAY
GEOPHYSICAL ENGINEERING
•
SEISMIC . . . GEOGRAPH . . . GRAVITY
MAGNETIC SURVEYS
•
2500 Bolsover Rd., P.O. Box 6557, Houston 5, Tex.

SAM D. ROGERS
Rogers Geophysical Company
Rogers Explorations, Sociedad Anonima
3616 West Alabama Houston 6, Texas

C. WHITNEY SANDERS
Consulting
Petroleum Geologist-Geophysicist
U. S. and European Exploration
1132 Bank of the Southwest Building
HOUSTON 2, TEXAS

TEXAS

RAYMOND L. SARGENT
Magnetometer Surveys
Interpretations
M & M Bldg.
HOUSTON 2, TEXAS

SIDNEY SCHAFER AND COMPANY
Geophysicists and Geologists
EXPLORATION CONSULTANTS
Domestic and Foreign
Sidney Schafer 2200 Welch Avenue
Jack C. Weyand Houston 19, Texas

HUBERT L. SCHIFLETT
States Exploration Company
Seismic, Gravity and Magnetic Surveys
5313 Richmond Road Highway 75 North
HOUSTON, TEXAS SHERMAN, TEXAS

H. B. SMYRL
Portable Seismograph, Inc.
706 Frost National Bank Bldg.
San Antonio 5, Texas

NELSON C. STEENLAND
Gravity Meter Exploration Company
Geophysicist
3621 W. Alabama Houston 27, Texas

R. C. SWEET
Geophysicist
1111 Bering Dr. Houston, Texas

Seismic Reviews Field Supervision
KIRBY J. WARREN
Geophysical Consultant
909 Continental Life Building
Fort Worth, Texas ED 2-9073

TEXAS

E. DARRELL WILLIAMS
Geophysicist
Specializing in Radiometric Exploration for Oil
3114 PRESCOTT ST., HOUSTON 25, TEXAS
PHONE MA 3-3991

JOHN H. WILSON
Exploration Consultant
1201 Sinclair Bldg.
FORT WORTH, TEXAS

CHARLES C. ZIMMERMAN
Geologist & Geophysicist
Keystone Exploration Company
2813 Westheimer Road
HOUSTON, TEXAS

WYOMING

Exploration Geology — Seismic Reviews
Evaluations — Seismic Supervision
JOHN F. PARTRIDGE, JR.
Consulting Geologist—Geophysicist
P.O. Box 258 — Room 211 O-S Building
Phones 2-6485 and 2-3328 CASPER, WYOMING

CANADA

R. E. DAVIS
Farney Exploration Company, Ltd.
830-8th Avenue West
CALGARY, Alberta, Canada

JOHN O. GALLOWAY
Petroleum Consultant
805 Eighth Avenue South West
AMherst 2-9018 CALGARY, ALBERTA

THEODORE KOULOMZINE
Geologist & Geophysicist
Koulomzine & Brossard Ltd.
P.O. Box 880, VAL D'OR Que. Canada.
Rm 905, 80 Richmond St. W. Toronto, Ont. Can.
Rm 1014, 132 St. James St. W. Montreal, Que. Can.

CANADA

GEORGE W. SANDER
Consulting Geophysicist
174 Douglas Ave. N., Oakville, Ontario — Phone VIctor 4-6345

W. F. STACKLER
Consulting Geophysicist
Phone CHery 4-7303
1937 25th Avenue S.W.
CALGARY, ALBERTA

For Information
On inserting your card
in the
Professional Directory

Write
Business Manager
Box 1536
Tulsa 1, Oklahoma

TRANSLATORS-SCIENTISTS WANTED

Proven ability to translate technical material into fluent English essential. Attractive full time or free-lance arrangement. All languages of interest, particularly Russian and Japanese. Send résumé to:

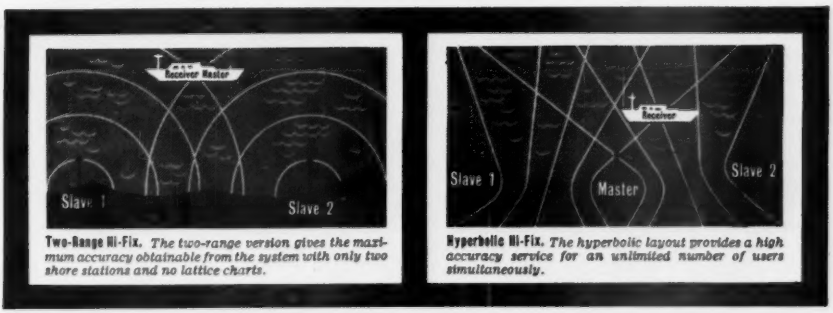
A-T-S, Inc.
Drawer 271, East Orange, N.J.

The Decca Navigator Company Ltd

HI-FIX

a new offshore survey system operating on high frequencies using lightweight equipment

HI-FIX equipment can be deployed in either the TWO RANGE or HYPERBOLIC forms by deploying the master station ashore or on the survey vessel, no equipment changes being required



Two-Range Hi-Fix. *The two-range version gives the maximum accuracy obtainable from the system with only two shore stations and no lattice charts.*

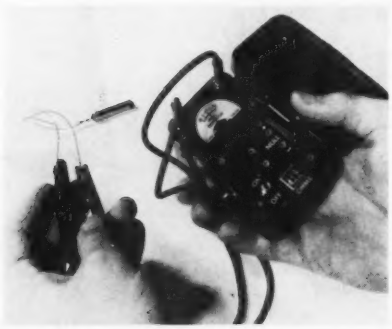
Hyperbolic Hi-Fix. *The hyperbolic layout provides a high accuracy service for an unlimited number of users simultaneously.*

HI-FIX offers for the first time a system that is:

precise, compact, lightweight, highly mobile and suitable for all forms of hydrography, offshore exploration, engineering survey, dredging, etc. free from the bugbears of 'beat notes', modulated transmissions, multiple frequencies, reference stations, wide bandwidths and interference. Based on the sound principles and employing the same techniques as the Decca Navigator System which is now used in its basic forms by more than 6,000 vessels, to say nothing of the many survey chains throughout the world. Hi-Fix is the answer for those small inshore areas where Hyperbolic or Two Range Decca is not justified on economic grounds. Normal Decca and Hi-Fix stations can be co-sited to give the precision pattern inshore (lane identified by the normal patterns) combined with the long working range of the normal Decca System.

THE DECCA NAVIGATOR COMPANY LTD · LONDON · ENGLAND

(Continued from page 10)



etics Corporation, Solana Beach, California.

The new low-resistance instrument is small enough to slip into a coat pocket, yet it performs the same functions as many testers that are several times larger.

To save expensive explosives and for safety reasons, all igniters should be checked on a tester before use. Manufacturers of devices used to set off explosions specify the electrical resistance the device should have to insure proper operation. A simple digital readout on this Kinetics instrument will indicate whether the device will operate properly or misfire. The new Kinetics' tester employs a sensitive bridge circuit. Maximum test current is limited to 10 milliamperes, so there is no danger of setting off igniters during the test.

The Kinetics instrument is designed for convenience. It may be held and operated in one hand. Power source is a self-contained battery. Weight of the whole unit is less than one pound. The null meter is a ruggedized, sealed unit that can stand rough handling in the field.

This Kinetics tester for field checking of explosive igniters may be used by missile test engineers, mining technicians, oil research teams, construction crews and all of the military services. It is sturdy and reliable and costs less than many comparable instruments. For more information, write to **Kinetics Corporation, 410 South Cedros Avenue, Post Office Box 427, Solana Beach, California.**

CONVERTER

The MAGAVERTER a completely static, solid state, precision analog to voltage to frequency converter has just been introduced by **Pioneer Magnetics Incorporated, 850 Pico Blvd., Santa Monica, California.** The MAGAVERTER uses only rugged, solid state components (no moving parts or vacuum tubes) to produce an output square wave whose frequency is directly proportional to the input voltage.

Excellent accuracy and stability are guaranteed. The MAGAVERTER will maintain an input-output linearity of $\pm$ ¼%. RED LINE MAGAVERTERS are linear to $\pm$ 0.1% with a temperature stability of better than 50 ppm/° C.

Eight standard models provide full scale output frequencies of from 30 cps to 25,000 cps. The maximum full scale frequency is adjustable by the customer over a 4/1 range with a built in attenuater. Standard units provide for input voltage ranges of 0-1, 0-10, 0-100 volts. Thus a model MI-1000-A MAGAVERTER will provide an output whose frequency can be set to vary linearly anywhere from 0 to 250 cps up to 0 to 1000 cps as the input signal is varied from 0 to 1 volt d.c.

Now an inexpensive, completely integral, solid state analog voltage to frequency transducer with extreme reliability is offered in a single package. The MAGAVERTER is outstanding for its light weight, small size, extreme simplicity and ease of installation. All models are assembled in a drawn steel Mil-T-27 can measuring 4-5/16″ x 3-11/16″ x 5-9/16″. The MAGAVERTER is designed for severe shock, vibration, and environmental conditions and is fully suited for missile and military applications.

(Continued on page 34)

CENTURY serves the world

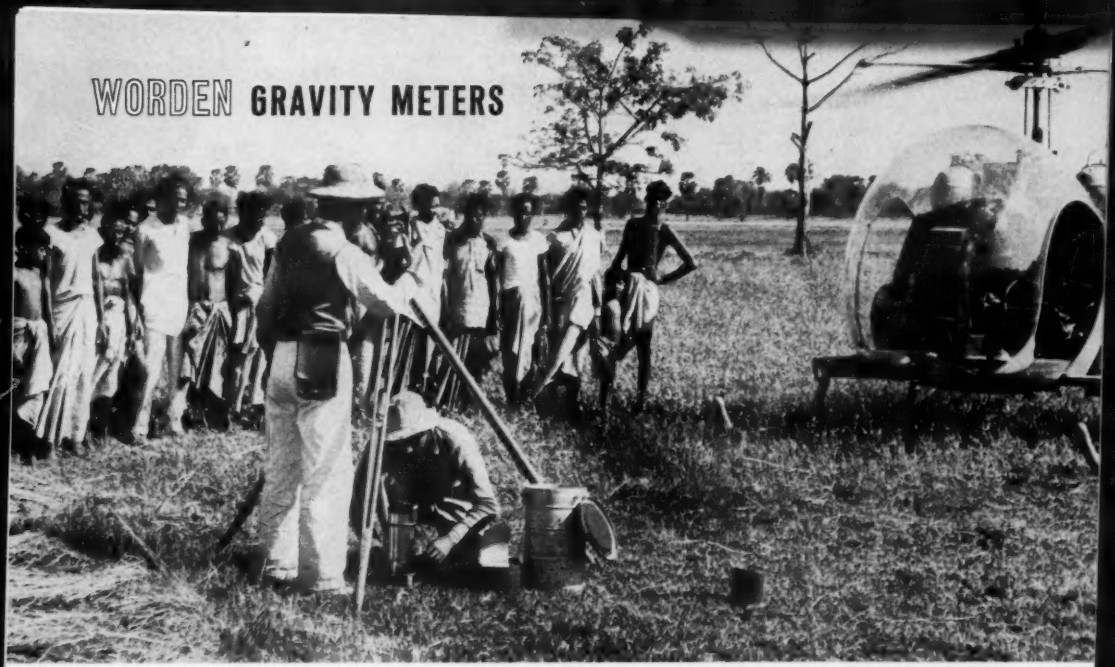
Century Geophysical Corporation, with its 44 geophysical units presently spread across the globe, is backed and strengthened by the research and development laboratories and the manufacturing facilities of Century Electronics & Instruments, Inc. These two affiliates are working partners in providing many industries with technical services and electronic instrumentation and equipment.

Seismic and gravity meter crew operations, review geophysical interpretations, velocity surveys, data center processing, uranium exploration logging and radiometric analysis are some of the general areas where Century has gained a large backlog of experience and wide acceptance.

Century's facilities are available to assist you in gathering, processing and evaluating scientific data anywhere in the world.

Century Geophysical Corporation *Century Electronics & Instruments, Inc.*

TWX TU-1407 — TULSA, OKLAHOMA



Take a NEW READING ON GRAVITY as an Effective, Economical Exploration Method

If you have not used Gravity, or if your use has been limited in recent years, it will pay you to reappraise the benefits of this fast, low cost exploration method. Instrumentation, operational techniques, and interpretation have been greatly improved enabling many operators to provide *specific and detailed* geologic information. Originally, the Gravity Method was thought of primarily as a means of determining *salt dome configurations*. Now, stratigraphic and structural information can be obtained such as: the areal extent and configuration of sedimentary basins; the maximum thickness and variation in thickness of basin sediments; regional structures within the basins; local and regional fault systems, including horsts and grabens, within the section; and local and regional thrust faults.

To obtain the best results, use the world's most proved gravity instrumentation . . .

There's a *WORDEN* Meter for Every Land Application

The MASTER and PROSPECTOR model *WORDEN* Gravity Meters provide the most demanding operating specifications ever achieved in portable meters. They retain the true portability and flexibility of the quartz element design plus the exclusive "Universal Compensation" feature which extends the temperature compensated range up to 6600 mgls. (world coverage). The MASTER is distinguished from the PROSPECTOR by a low power Temperature Stabilizer, which maintains a nearly constant internal temperature in spite of extreme outside thermal shocks. Both meters are available in Standard and Geodetic models.

The PIONEER is ideally suited for gravity programs in areas of limited latitude and temperature variations and where the need for less frequent base ties exists. Also available in Geodetic model.

The EDUCATOR gravity meter is intended to meet the needs of educational or training programs where the required tolerances are much wider than for commercial programs.

Specifications for the respective *WORDEN* Gravity Meters are shown at right . . . contact TI's Gravity Department for additional information.

Select Your *Worden* Gravity Meter from the widest combination of models and ranges in the industry!

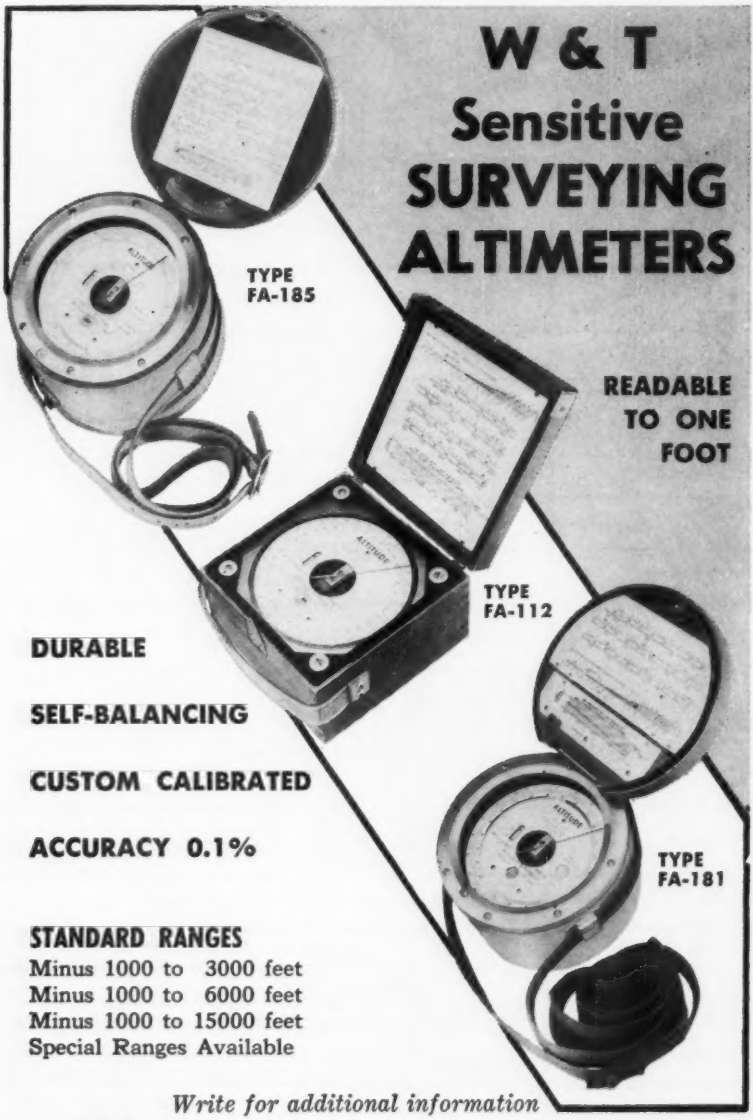
When requesting a quotation, copy the specification categories in this column and specify the values desired from those found under the respective meters.	the *Master*	the *Prospector*	the *Pioneer*	the *Educator*
Minimum Recommended Operating Range—Specify to nearest 100 mgls.* plus latitude and elevation indication	3000 mgls.	3000 mgls.	2400 mgls.	Limited . . . Will be at least 1600 mgls.
Minimum Total Operating Range (Reset) —Specify to nearest 100 mgls.*	5200 mgls.	5200 mgls.	4000 mgls.	Limited . . . Will be at least 2000 mgls.
Small Dial Range	800 Dial Divisions x Small Dial Constant (2200 on Special Order)	800 Dial Divisions x Small Dial Constant (2200 on Special Order)	800 Dial Divisions x Small Dial Constant	800 Dial Divisions x Small Dial Constant
Small Dial Constant—Specify constant desired*	Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available)	Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available)	Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available)	0.10-1.00 mgl./ Dial Division
Small Dial Calibration Linearity over full range	1 part in 1000	1 part in 1000	1 part in 1000	1 part in 1000
Small Dial Reading Accuracy	0.1 of Small Dial Division	0.1 of Small Dial Division	0.1 of Small Dial Division	0.1 of Small Dial Division
External Temperature Control	Temp. Stabilizer requires 1.00 watts power for a 100° F. differential. Four Rechargeable "D" Size Batteries maintain 90° F. differential for 10 hours and are mounted in removable pack on side of meter. Any 4.5 to 12 volt DC source may be substituted.	None	None	None
Small Dial Mechanism	Self counting, read from top and directly coupled (no gears for backlash) with screw which contacts quartz measuring spring.		Side and top reading, directly coupled (no gears for backlash) with screw which contacts quartz measuring spring.	
Large Dial Range — Specify range desired*	800 Dial Divisions x Large Dial Constant			Geodetics not available
Large Dial Constant	Standard 6.5 to 12.0 mgls./D.D.			Geodetics not available
Large Dial Calibration over full range (8 turns)	Curve furnished with values accurate to one part in 1000—measured over full range (8 turns).			Geodetics not available
Size, Inches: Diameter Height	7" 14"	7" 14"	5½" 10½"	5½" 10½"
Weight, Pounds: Net Including carrying case	9¾ lbs. 18 lbs.	7½ lbs. 15¾ lbs.	5⅛ lbs. 12 lbs.	5⅛ lbs. 12 lbs.
*Price of meter is determined mostly by the Ranges and Dial Constant Specified.				

Write for Bulletin No. GM-206

***WORDEN* Gravity Meters Are Made Exclusively By**

TEXAS INSTRUMENTS
INCORPORATED
GEOSCIENCES & INSTRUMENTATION DIVISION
3609 BUFFALO SPEEDWAY • HOUSTON 6, TEXAS • CABLE: TEXINS

W & T Sensitive SURVEYING ALTIMETERS



DURABLE

SELF-BALANCING

CUSTOM CALIBRATED

ACCURACY 0.1%

STANDARD RANGES
Minus 1000 to 3000 feet
Minus 1000 to 6000 feet
Minus 1000 to 15000 feet
Special Ranges Available

Write for additional information

WALLACE & TIERNAN INCORPORATED
25 MAIN STREET, BELLEVILLE 9, NEW JERSEY
IN CANADA: WALLACE & TIERNAN LTD., WARDEN AVE., TORONTO 13, ONT.

A-118.42

SEISMOGRAPH SURVEYS*

**long and short term contracts*

C. N. PAGE A. E. "SANDY" McKAY C. J. LOMAX

Central Office
Continental Life Bldg.
Fort Worth, Texas

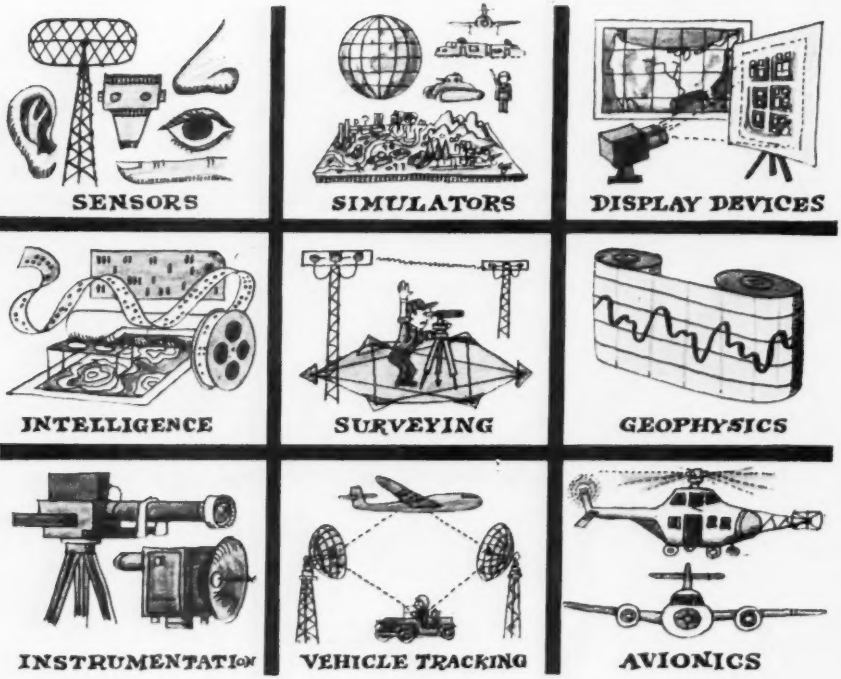
Division Offices

WEST TEXAS
Midland, Texas

MID-CONTINENT
Tulsa, Okla.

ROCKY MTS.
Denver, Colorado

Foreign Affiliate: namco INTERNATIONAL



Aero Service Corporation
Oldest Flying Corporation in the World
announces the formation of

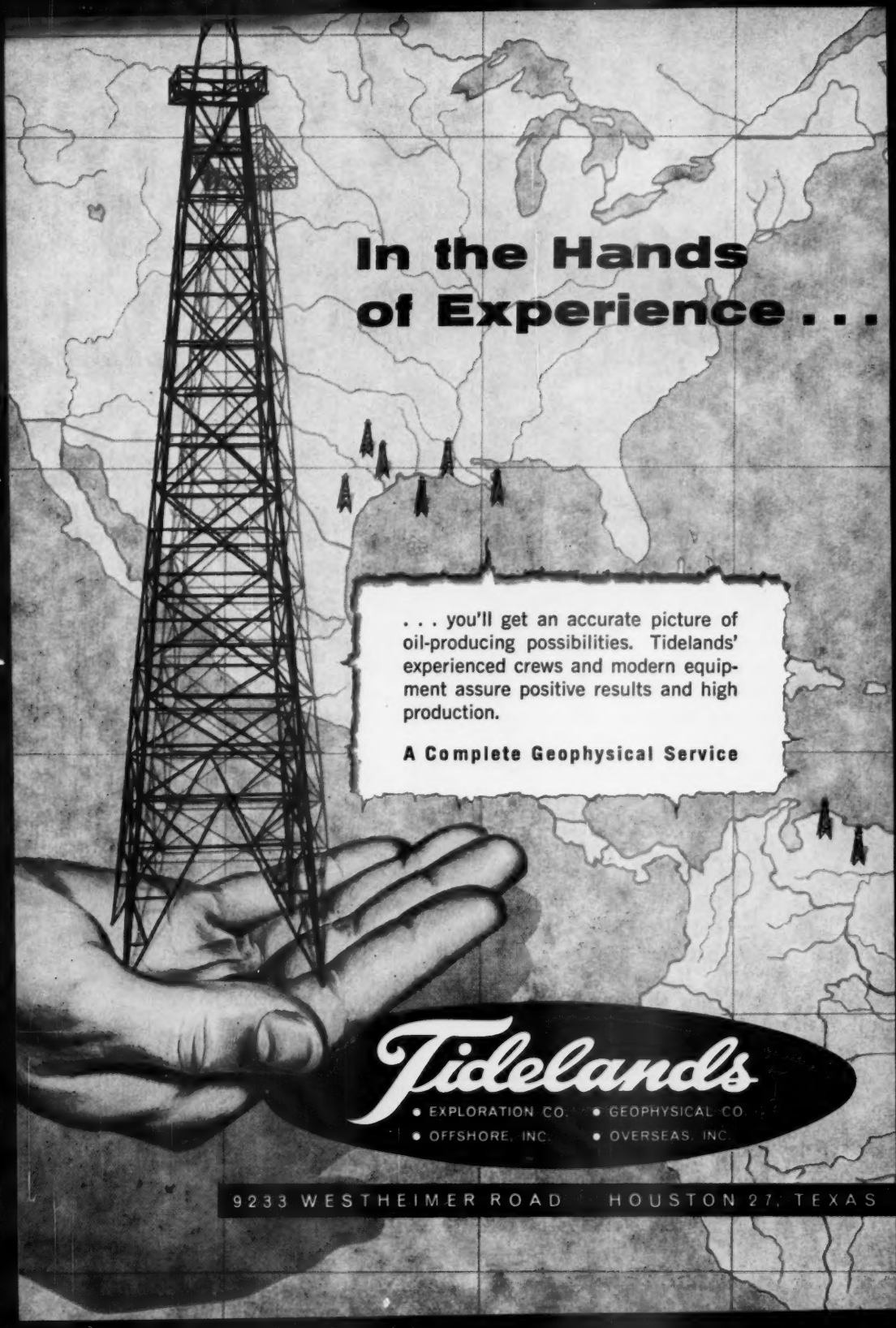
AERO SYSTEMS ENGINEERING DIVISION

. . . a modern, fully equipped facility staffed to undertake services, research, and development in fields related to photogrammetry, geophysics, special simulators, training devices, avionic tests, and data handling and analysis. The new AERO Division offers the benefits of 41 years of experience by Aero Service Corporation, authority on airborne geophysics and cartographic sciences. We invite you to write for our facilities report.

Partial list of clients served by Aero on Department of Defense prime and sub-contracts

AIR MATERIEL COMMAND
CORPS OF ENGINEERS, U.S. ARMY
STRATEGIC AIR COMMAND
U.S. NAVY BUREAU OF WEAPONS
EASTMAN KODAK COMPANY
IBM CORPORATION
RADIO CORPORATION OF AMERICA
RAMO-WOOLDRIDGE
WESTERN ELECTRIC CORPORATION

Aero
SYSTEMS ENGINEERING
A NEW DIVISION OF
AERO SERVICE CORPORATION
210 East Courtland Street
Philadelphia 20, Pennsylvania

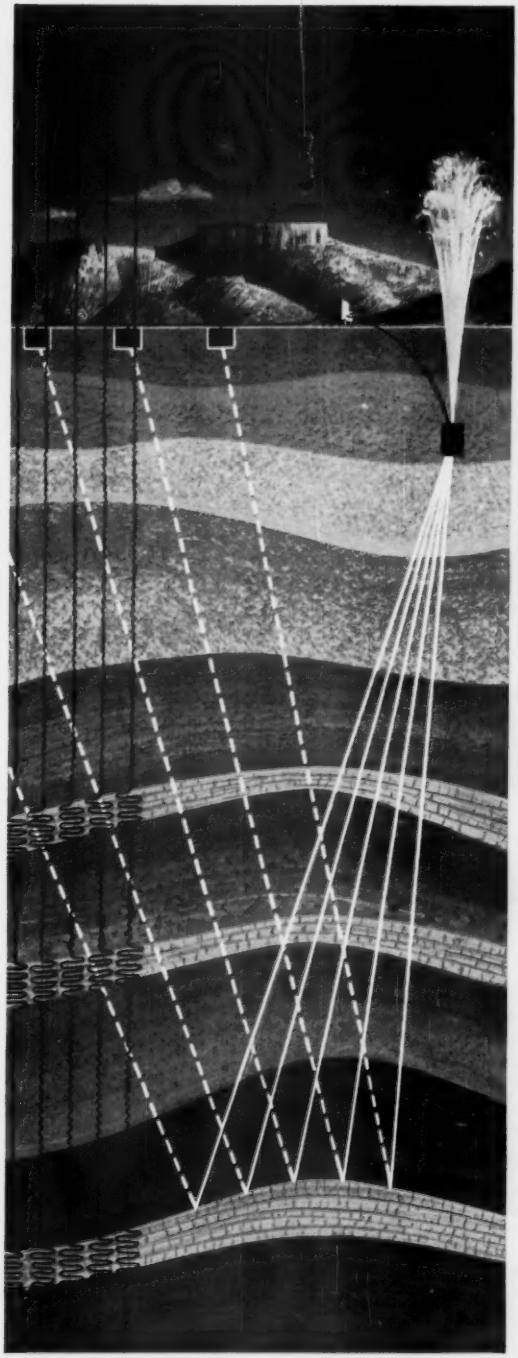

In the Hands of Experience . . .
. . . you'll get an accurate picture of oil-producing possibilities. Tidelands' experienced crews and modern equipment assure positive results and high production.
A Complete Geophysical Service
Tidelands
• EXPLORATION CO. • GEOPHYSICAL CO.
• OFFSHORE, INC. • OVERSEAS, INC.
9233 WESTHEIMER ROAD HOUSTON 27, TEXAS

FOR WORLDWIDE GRAVITY AND MAGNETIC SERVICES

rely on Robert H. Ray Companies. Each contract is backed by experience gained from more than twenty years of foreign and domestic operations—research and development in instrumentation and interpretation. Lower cost per station and fast, accurate service from skilled crews are standard benefits you get from the Robert H. Ray Companies. Seismic Services, including Geograph, are also available anywhere in the world. Let us explain how each of these techniques will fit into your Geophysical program.

For Geograph in Europe and the French Zone contact GEOGRAFRANCE, 48 Blvd. de Latour-Maubourg, Paris 7e.

ROBERT H. RAY GEOPHYSICAL COMPANIES
2500 Bolsover, Houston 5, Texas



Belt or tape—for accurate magnetic recording of seismic data ask your supplier for

REG. U.S. PAT. OFF.

SCOTCH BRAND

In geophysical work, as in dozens of other sciences, "SCOTCH" BRAND Magnetic Products provide the reliable response needed for accurate data acquisition.

Makers of some of the most sensitive tapes used in instrumentation, "SCOTCH" BRAND has pioneered in developing the basic magnetic products which leading manufacturers of seismographic systems include in their own catalogues. Belt or tape—AM or FM recording—for top output ask your seismographic supplier for "SCOTCH" BRAND—and compare the results.

"SCOTCH" BRAND MAGNETIC PRODUCTS
fo geophysical recording

MINNESOTA MINING AND MANUFACTURING COMPANY
...WHERE RESEARCH IS THE KEY TO TOMORROW

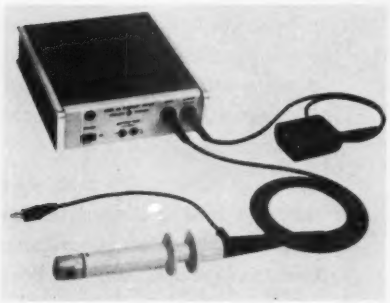
"SCOTCH" is a registered trademark of 3M Company, St. Paul 6, Minnesota. Export: 99 Park Avenue, New York, N. Y. In Canada: London, Ontario.

(Continued from page 24)

The versatility of the MAGAVERTER readily adapts it to a wide variety of precision analog to digital conversion tasks. With a digital counter the MAGAVERTER serves as a digital voltmeter. For longer time periods the combination will act as a noise insensitive integrator giving a digital readout of flows, pressure, volt seconds, etc. Combined with a MAGACYCLER (Pioneer's Frequency to Voltage Converter) the MAGAVERTER can be used to give a frequency output which is any desired multiple or fraction of the MAGACYCLER input. This combination is also used for wide range frequency multiplication.

AC CURRENT PROBE

A unique instrument which converts ac current to ac voltage for direct reading on a conventional oscilloscope or ac voltmeter is now available from Hewlett-Packard Company.



The instrument, Model 456A AC Current Probe, has a probe which simply clamps around the current-carrying wire, providing a voltage output which is quickly and easily read on a VTVM or oscilloscope. The instrument's 1 mv to 1 ma unity conversion permits direct readings in milliamperes on voltmeters or oscilloscopes.

The Model 456A measures current without direct connection to the test circuit and with no appreciable circuit loading. Typical applications include measurements on transistors, vacuum tubes and logic circuits.

The instrument's wide bandwidth (20 cps to 15 mc) also permits oscilloscope viewing of complex current waveforms with rise times as fast as 0.08 microseconds. The Model 456A simplifies ac current measurements of up to one ampere at frequencies up to 5 mc and at least 100 ma from 5 mc to 15 mc.

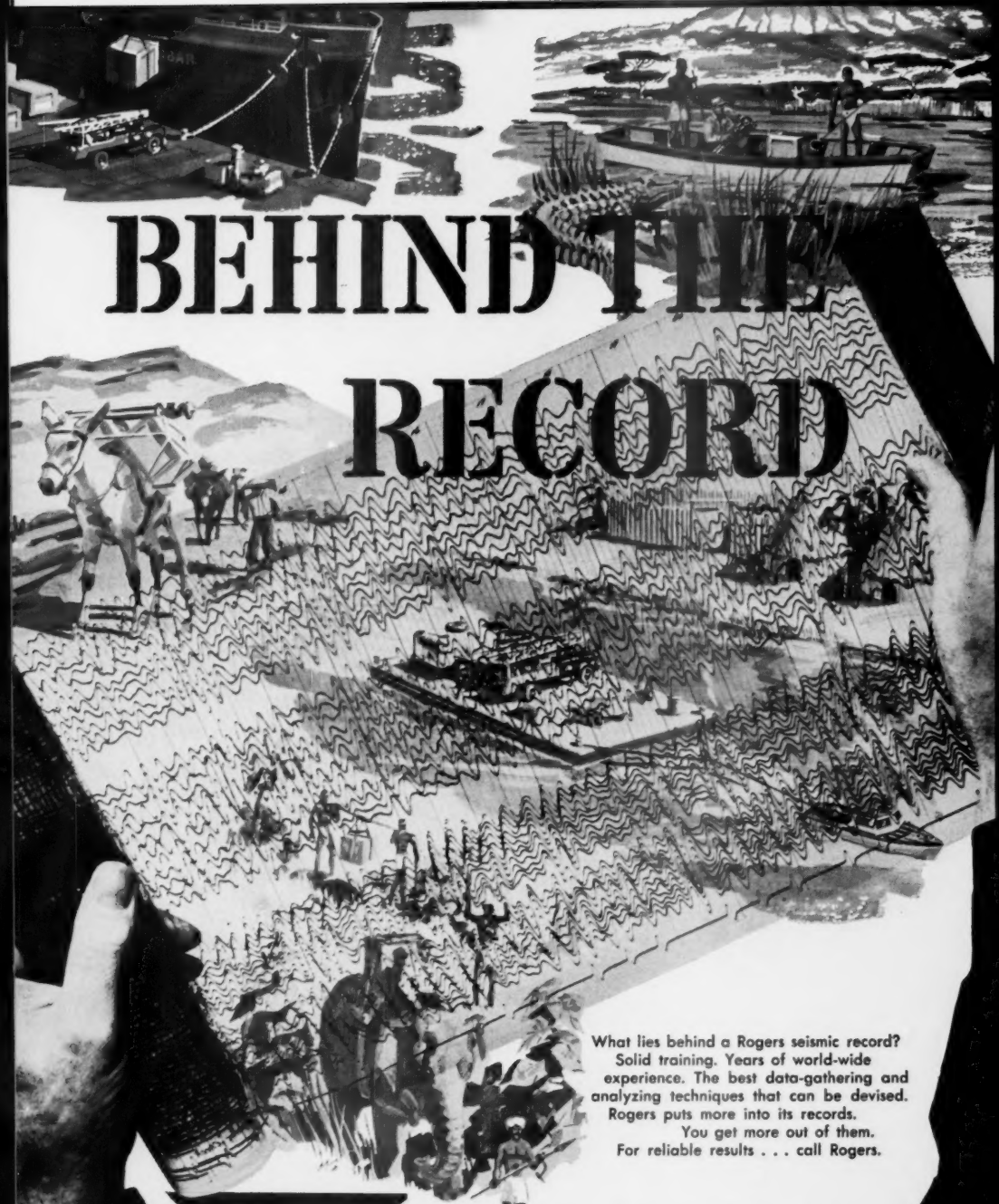
Model 456A is a compact unit weighing only 3 pounds. **Hewlett-Packard Company, 275 Page Mill Road, Palo Alto, California.**

SEISMIC TIMER

MODEL 117 SEISMIC TIMER, developed by **DynaMetric, Inc., 2955 East Colorado Blvd., Pasadena, California,** features

direct, totalized time reading for measuring hammer induced shock wave velocities in soils. It allows shallow exploration of

(Continued on page 38)



What lies behind a Rogers seismic record?
Solid training. Years of world-wide experience. The best data-gathering and analyzing techniques that can be devised.
Rogers puts more into its records.
You get more out of them.
For reliable results . . . call Rogers.

Rogers *Geophysical Companies*

3616 WEST ALABAMA • HOUSTON, TEXAS

FOREIGN OFFICES

Edificio Republica • Caracas, Venezuela
Mogadiscio • Somalia
34 Ave. des Champs Elysees • Paris, France
1-3 Arlington St., St. James's • London S.W. 1, England

ROGERS' CREWS GO EVERYWHERE

Kodak

SEISMOS

provides you with informations from the underground

Seismos G.m.b.H.,
Wilhelm-Busch-Straße 4,
Hannover, Germany.
Phon 7 08 31
Telex 09 22419

He has always thought a pick was the tool with which the Erie Canal was dug.

He thinks "D Max" is the name of a guy who might have been called "Dave" but wanted a classier handle.

Dr. F. W. Spangler (left) meets R. C. Hilton, senior geophysicist in charge of geophysical data processing for Shell Oil Company, Houston. Purpose of the visit is to familiarize Dr. Spangler directly with the ideal characteristics which Shell desires in a polyester recording film for use in the Reynolds Plotter. Dr. Spangler is an assistant superintendent of Kodak's Film Emulsion Division.

With the switch to thin, rugged Estar Base that eliminates troublesome dimensional change, Fred Spangler had to decide what inherent maximum density to give the new **Kodak Linagraph Recording Film.** Dick Hilton needs more from a film than that it shouldn't be troublesome. He doesn't talk Fred's "D Max" language. He seeks a certain appearance to which his perceptual process best responds in picking a "pick" from the corrected cross-section which the Plotter puts on the film. Spangler learned plenty from him and from others with other instrumentation and other perceptual patterns of translating photographic images into technical intelligence.

Photorecording Methods Division

EASTMAN KODAK COMPANY, Rochester 4, N.Y.

(Continued from page 34)

earth structures to depths of fifty feet, without drilling. Size 7 x 7 x 11 inches, weight 12 pounds. The method, a simplified adaptation of techniques developed long ago in oil exploration, is based on measurement of the velocity of shock waves moving through surface and subsurface materials. Shock waves are generated by sledgehammer blows against a steel plate. Timer measures arrival of the waves at a sensitive geophone. The battery-powered instrument, which reads shock wave travel time, totalized directly in milliseconds, weighs only 12 pounds.

RECORDING pH METER

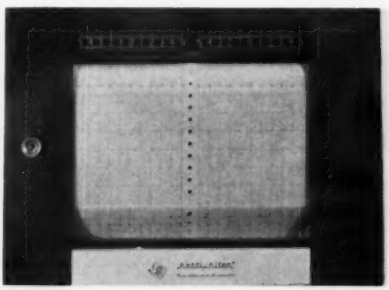
For the first time, a combined pH meter and strip chart recorder is available at a price lower than most conventional pH meters alone!

This sensational instrument utilizes an electronically modulated amplifier that compensates for line voltage fluctuations and uses standard radio tubes. A strip chart recorder forms the front panel of the instrument and contains a 63 ft. roll of chart paper that will last for 31 days at 1 inch per hour. Other chart speeds are available up to 16 inches per hour by a simple gear change. A pressure sensitive coating is used on the chart paper so that annoying ink and clogged pen problems are eliminated. Connections for insertion of a platinum resistance thermometer provide automatic temperature compensation. A switch on the front panel permits disconnection of the chart drive so that the instrument becomes an indicating pH meter. The Analytical Revolutionary pH Probe Unit provides a unitary glass electrode system completely protected by polyethylene which makes possible pH monitoring that heretofore has been impractical because of complicated installation or excessive instrument costs.

For further information, send for illustrated brochure No. 3-R to **Analytical Measurements, Inc., 585 Main Street, Chatham, New Jersey.**

STRIP-CHART RECORDERS

Flush-mounting models of the "recti/riter" galvanometric recorders for panel installations have been announced by Texas Instruments Incorporated. The new instruments join TI's existing line of portable strip chart recorders which feature rectilinear recording motion.



The flush-mounting "recti/riter" recorders are available in both single and dual-channel models. They were developed by the Instrumentation product group of TI's Geosciences & Instrumentation division in Houston.

The new instruments have swing-out chart carriages and a slide-out chassis for extra accessibility. In addition, they have an illuminated scale for greater visibility at a distance. A zero adjustment provides for zero settings over the entire scale as well as zero suppression above or below scale.

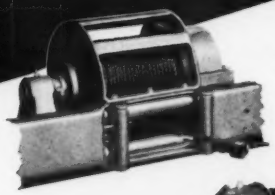
The Instrumentation product group of Texas Instruments is engaged in the design, development, and manufacture of electronic instrumentation, including industrial recorders, automation equipment, supervisory control systems, and geophysical equipment.

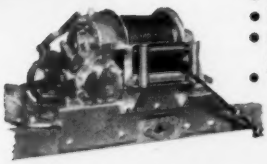
Texas Instruments Incorporated, 3609 Buffalo Speedway, Houston 6, Texas.

(Continued on page 46)

KING WINCHES

. . . for 'Jeep' vehicles, International*, Chevrolet, GMC, Ford, Land Rover and others.



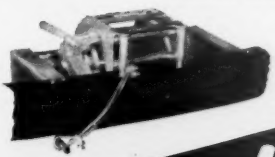


COMPLETE, READY-TO-INSTALL KING FRONT-MOUNT WINCH ASSEMBLIES FEATURE:

- winch side arms to reinforce truck frame
- bronze-bushed, 4-way cable guide rollers
- cable drum guard
- heavy-duty pipe bumper
- needle-bearing, universal-joint spline-shaft drive assembly
- Timken bearings on worm

**King Winches for International trucks are available through International-Harvester dealers.*

King Winches keep you moving through the most difficult terrain . . . you get action where there's no traction with dependable pulling power. King power winches have pulling capacities of 8,000 to 19,000 lbs.



Koenig

ALL-STEEL CABS FOR 'Jeep'® UNIVERSALS

FULL AND HALF CABS

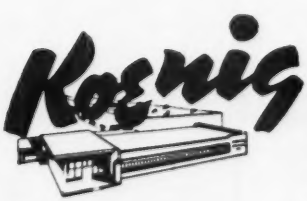
Model 550 Koenig Full Cab and Model 151J King Winch on CJ-5 'Jeep' Universal.

Koenig cabs and King Winches for 'Jeep' vehicles are available through all authorized 'Jeep' vehicle dealers. Write for free descriptive literature.

KOENIG ALL-STEEL CABS HAVE THESE SUPERIOR FEATURES:

- PROTECTION
- SAFETY
- COMFORT
- CONVENIENCE

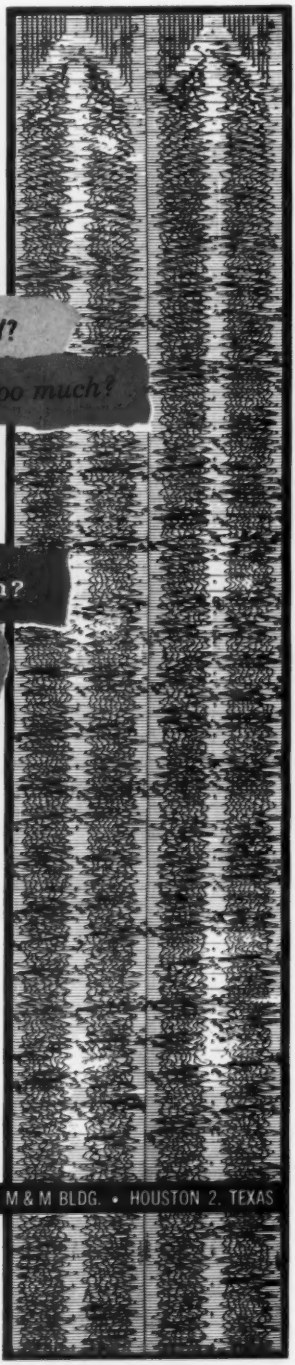
Roll-down windows, full opening . . . full panelboard head lining and masonite door lining . . . safety glass throughout . . . all-steel welded construction . . . door locks.



IRON WORKS, Inc.

P.O. BOX 7726R • HOUSTON 7, TEXAS

DO YOU HAVE THESE HEADACHES WITH SEISMIC RECORDS?



ORIGINAL RECORDS DISCOLOR QUICKLY?

duplicate and security copies cost too much?

adequate insurance impossible?

record sizes not uniform?

too many records to handle and store conveniently?

By duplicating your field documents on a 16mm microfilm and exposing each record individually in its entirety, Industrial Photographers can: furnish you with a continuous profile record section that is uniform in size and color; eliminate 98% of the bulk of your seismograph records; supply a negative that lasts indefinitely and from which duplicates can be made for just a few cents a copy. When reproduced on 16mm microfilm, duplicate prints of the original can be enlarged to full or half scale, or to a Seismo Copy* record section.

For immediate service or for descriptive details, write or call:

THE INDUSTRIAL PHOTOGRAPHERS COMPANY

CApitol 2-1973 • 301 M & M BLDG. • HOUSTON 2, TEXAS

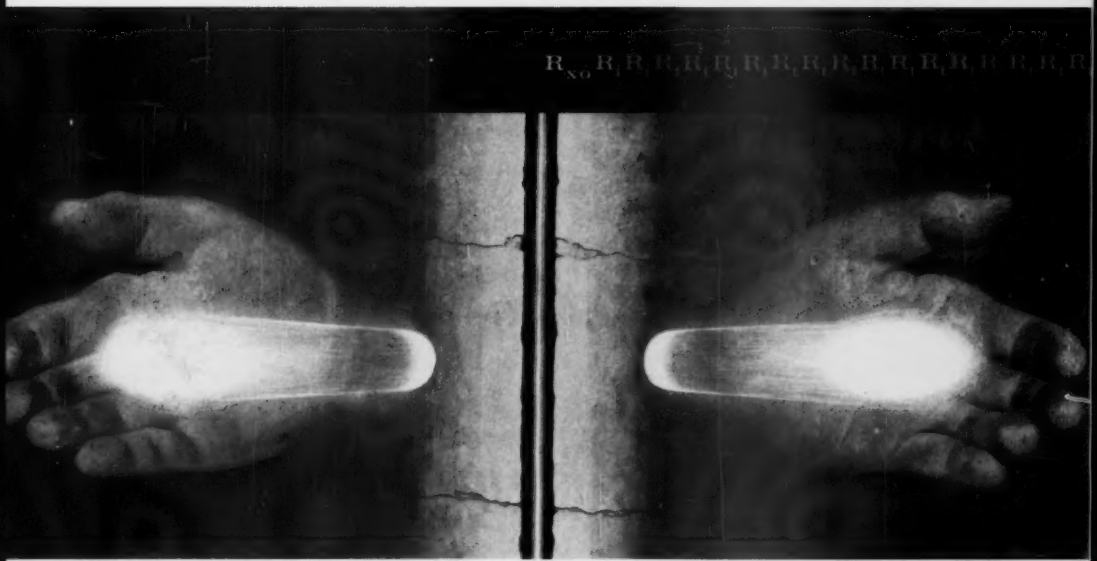
Reproduction Specialists for the Oil Industry

All record reproduction under the supervision of an experienced geophysicist.

Seismo Copy is a process especially designed for geophysicists. Seismo Copy gives you a continuous composite of the record section on a reduced scale without splicing. Patent pending.

The New Schlumberger Deep Induction Log

reaches twice as deep to give twice the contrast between water and oil



Engineered to overcome deep invasion, the new Schlumberger Deep Induction Log retains all the advantages of the Induction-Electrical Log . . . symmetrical response, thin bed definition, detail for correlation, simultaneous recording with 16″ SN and SP . . . *plus* an investigation twice as deep which gives twice the contrast between water and oil.

Your Schlumberger engineer will be glad to explain this new service in detail. It's another product of Schlumberger research and engineering to meet the challenge for greater efficiency in oil finding.

THE EYES OF THE OIL INDUSTRY®

SCHLUMBERGER

POINTING THE WAY FOR THE DRILL

IX

Your complete geophysical service company

Independent Exploration Company service is more complete than ever. In addition to its unparalleled experience and ability in traditional geophysical survey techniques IX offers you a wide range of skill and highly specialized equipment for gravity meter surveys, weight dropping surveys, offshore and inland marine surveys.

To get more usable data for your dollar invested in exploration, call in . . .

INDEPENDENT EXPLORATION CO.

Geophysical Surveys

1964 West Gray • Houston, Texas

Cable Address: **Independex**

PARIS / LONDON / ALGIER / CASABLANCA / MADRID / TRIPOLI

Western Conducts More Marine Seismic Surveys Than All Other Contractors Combined!

Every year since 1954, Western Geophysical Company boats have done well over half of ALL contract offshore seismic explorations in the world.

This record reflects the considered judgment of many of the most respected people in the petroleum industry on the competence of Western men, techniques and instrumentation. When you consider your next geophysical survey, let us tell you more about the Western services that have earned and held such confidence.

Additionally,
Western's land seismic parties
and gravity crews
are at work on four continents.

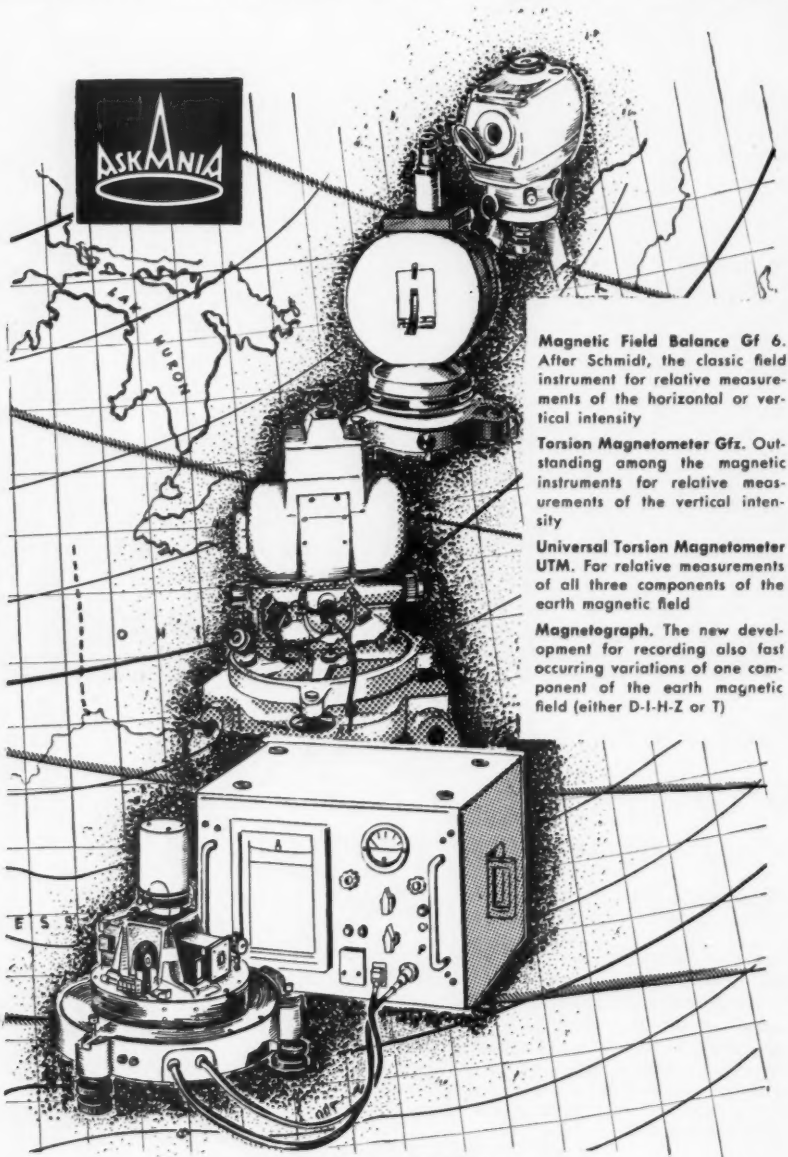
Western
GEOPHYSICAL COMPANY
A SUBSIDIARY OF LITTON INDUSTRIES

Principal Office: 933 NORTH LA BREA AVENUE, LOS ANGELES 36, CALIFORNIA

AFFILIATE AND REGIONAL OFFICES THROUGHOUT THE WORLD

Please mention GEOPHYSICS when answering advertisers

ASKANIA Magnetic Instruments for precise determination of magnetic anomalies



Magnetic Field Balance Gf 6. After Schmidt, the classic field instrument for relative measurements of the horizontal or vertical intensity

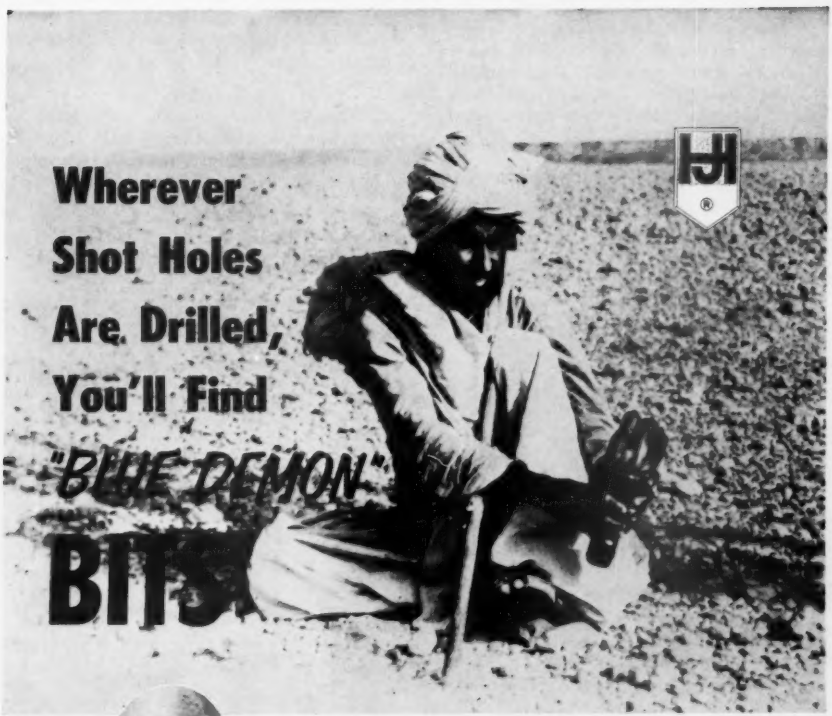
Torsion Magnetometer Gfz. Outstanding among the magnetic instruments for relative measurements of the vertical intensity

Universal Torsion Magnetometer UTM. For relative measurements of all three components of the earth magnetic field

Magnetograph. The new development for recording also fast occurring variations of one component of the earth magnetic field (either D-I-H-Z or T)

ASKANIA-WERKE

U. S. Branch Office & Service Dept. • 4913 Cordell Ave., Bethesda, Maryland



U.S. Patent Nos.
2,615,684
2,666,622
2,695,158
2,783,973
2,831,657
2,859,942
2,890,020
2,894,726

With the problems of shot hole drilling pretty much the same the whole world over, it takes a bit that's as rough and tough in Tunis or Alberta . . . as in Texas or the Argentine . . . which will provide the most efficient performance at an economical per-foot cost.

Patented Hawthorne "Blue Demon" Bits have proven inherently better for international operations because:

- Basically high quality of original design and manufacture assures superior performance every time . . . at consistently competitive price . . .
- Replaceable blade feature provides factory-controlled "on-the-drill" bit service ANYWHERE . . .
- Interchangeability of size and formation-type of blades in the same bit body tremendously increases bit versatility . . . reduces inventory needs . . .
- Vastly reduced bulk and weight requirements over competitive products offer additional savings in handling, shipping and storage costs . . .

Available in popular fractional sizes to fit all types of shot hole drills.

WRITE FOR ILLUSTRATED CATALOG

HERB J. HAWTHORNE INC.

Cable Address: HAWBIT • P. O. Box 7306 • Houston 8, Texas

228

(Continued from page 38)

FILM RECORDER/VIEWER

A new automatic-processing 16 mm film recorder and viewer for use with either galvanometers or a CR tube is announced by Geotech for recording data as high as 15 kc. The versatile instrument is called the DEVELOCORDER.

From 1 to 16 galvanometers can be used to record multi-channel data from DC to 20 cps, or up to 150 cps on special order. With a CR tube, DC to 15 kc data can be recorded, as well as intensity-modulated spectrograms, Lissajous patterns, and other presentations.

From 4 to 32 continuous hours of data can be recorded on self-contained 200′ reels of standard microfile film at speeds of 3 to 20 cm/min. Self-contained circulating chemicals and a blower process the film automatically. The DEVELOCORDER then displays the data magnified × 10 on its 6″ × 17″ viewscreen within 2 to 20 minutes after recording, using the 2-directional, variable-speed viewing drive.

The date, time, and film number are optically printed on the film during recording. Time mark pulses are fed directly to the galvanometers. A plastic grid template can be placed over the viewscreen for data measurements. Film trace width is .05 mm. Linearity is better than 2%. Weight is 175 pounds. **The Geotechnical Corporation, 3401 Shiloh Road, Garland, Texas.**

DRILLING MUD

Baroid Division, National Lead Company, has introduced QUIK-GEL, a research developed high-yield bentonite especially for seismograph and water well drilling muds.

QUIK-GEL makes twice as much mud, in fresh water, as can be made with standard bentonites. Therefore, only half as much QUIK-GEL is required to drill each hole.

QUIK-GEL is easier to mix and disperses more rapidly. Holes can be drilled quicker and cheaper.

QUIK-GEL thickens fresh water drilling fluids fast, improves wall building, reduces water loss, lubricates drill pipe and bits, reduces transportation and handling costs, saves time, reduces mud and chemical costs, and can be used effectively with other Baroid drilling mud products.

QUIK-GEL is available from Baroid Stores and from many explosive and seismic supply firms.

WHEN YOUR CONTRACT IS WITH GENERAL

General's geophysical services – exploration techniques, equipment design, interpretation – are expressly coordinated to give you a better return on your oil prospect investment. **THE PROOF?** You enjoy a higher percentage of successful exploration.

General
GEOPHYSICAL COMPANY
HOUSTON CLUB BUILDING • HOUSTON, TEXAS

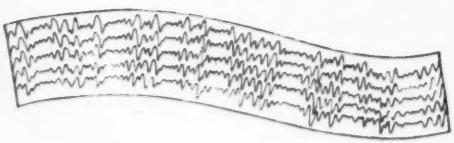
In Canada: 10509 81st Avenue, Edmonton, Alberta, Canada
General Geophysical Company de France (SARL), 4 Square Rapp
General Geophysical Company de Venezuela, C. A., Apartado 1871
General Geophysical Company (Bahamas) Ltd., Bogota, Colombia

25 YEARS OF
1923 GENERAL GEOPHYSICAL CO. 1948
SUCCESSFUL SERVICE

! WHEN YOUR CONTRACT IS WITH GENERAL, THE PERCENTAGE FOR SUCCESSFUL EXPLORATION IS IN YOUR FAVOR

COMPETENCE . . . *based on twenty-eight years of professional service.*

SEISMIC EXPLORATIONS INC.



SEI OFFERS . . . a group of experienced personnel—operational and staff.

Equipment and technical standards controlled by our own laboratory.

Leaders in modern methods of acquisition of seismic data and its interpretation in terms of geologic structure.

SEISMIC EXPLORATIONS, INCORPORATED

HOUSTON, TEXAS

Midland Shreveport Denver

Foreign Affiliate : Compagnie Reynolds de Geophysique,
9 Rue du Marquis de Coriolis, Paris, France
B. P. 14 Hussein Dey, Alger, Algeria

Please mention GEOPHYSICS when answering advertisers

PORTABILITY
that pays for itself!

EXPLORER
24-Trace All-Transistorized Seismograph

The EXPLORER* Seismograph is setting economy and performance records in SUMATRA, PERU, COLOMBIA, MEXICO, FRANCE, CANADA, MISSISSIPPI, and SOUTH LOUISIANA.
This Seismograph FIRST can do the same for you by . . .

- Cutting recording and support personnel in half.
- Halving time at and between recording set-ups, thus doubling production and proportionately reducing cost per profile.
- Giving you a wide operational range of frequencies from high resolution to refraction . . . wide selection of AGC, fixed, and TVG gain controls.
- Offering unequalled portability for "back-packed" or helicopter operations.

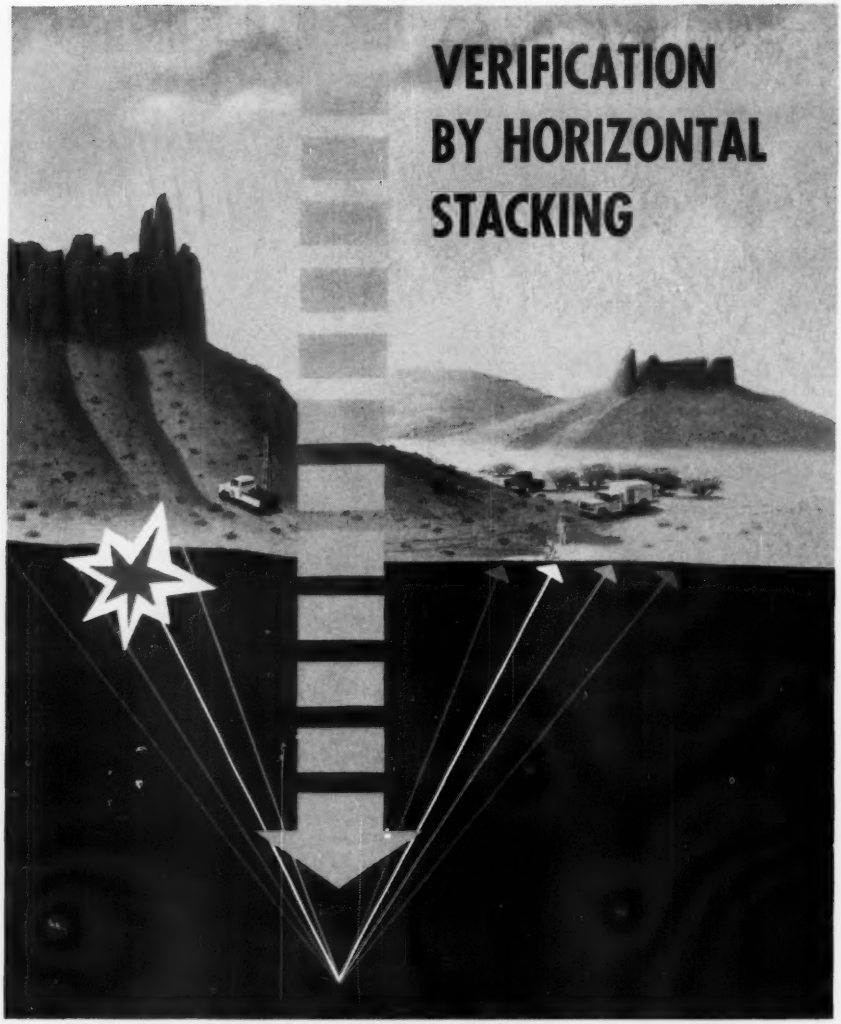
The EXPLORER Seismograph pays for itself in *reduced operating costs* and *increased production* . . . let a TI seismic engineer supply you with proof.

* A trademark of Texas Instruments

TEXAS INSTRUMENTS
INCORPORATED
GEOSCIENCES & INSTRUMENTATION DIVISION
3609 BUFFALO SPEEDWAY • HOUSTON 6, TEXAS • CABLE: TEXINS

341

Please mention GEOPHYSICS when answering advertisers



For information on the Petty Stacking technique write to

Petty
GEOPHYSICAL ENGINEERING CO. TRANSIT TOWER SAN ANTONIO CApitol 6-1393

Petty's patented* horizontal stacking technique verifies each subsurface point with multiple ray paths. Since only the reflection point is common to all, noise is greatly reduced and maximum record clarity is assured.

*U. S. Patent No. 2,732,906

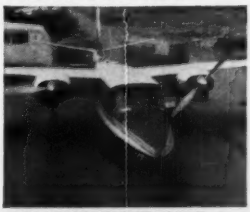
Please mention GEOPHYSICS when answering advertisers

ABEM

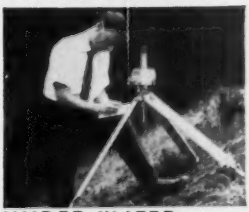
carries out

GEOPHYSICAL INVESTIGATIONS

FROM THE AIR



ON THE GROUND



UNDER WATER

IN MINES AND BOREHOLES

for

ORE PROSPECTING
OIL EXPLORATION
AND
CIVIL ENGINEERING

ABEM

GEOPHYSICAL INSTRUMENTS

for

- Airborne EM and Magnetic Surveys
- Ground EM, Magnetic, Electric, Seismic, and Gravimetric Surveys
- Underwater Seismic Surveys
- Underground Magnetic Surveys

For further details about these geophysical services and instruments write to

THE ABEM COMPANY

DANDERYDSGATAN 11, STOCKHOLM, SWEDEN,
or contact your nearest ABEM agent

U.S.A.	ENGLAND	CANADA	FRANCE	SOUTH AFRICA	AUSTRALIA
Geophysical Instrument and Supply Co., 1616 Broadway, Denver 2, Colorado.	Craelius Company Limited, 11 Clarges Street, London, W.1.	Moreau Woodard & Co., Ltd., 1880 O'Connor Drive, Toronto 16, Ontario.	S.A. Craelius, 92 Av. des Champs-Elysées, Paris 8e.	Norse Industries (Pty.), Ltd., 221 Cullman Building, Simmonds Street, P.O. Box 9549, Johannesburg.	J. J. Masur & Co. Pty. Ltd., John Street, P.O. Box 48, South Melbourne, S.C.5.

for BETTER SEISMOGRAPH SERVICE

TEXAS SEISMOGRAPH CO., INC.
1502 EIGHTH • WICHITA FALLS, TEXAS

COMPANY MEMBERSHIP

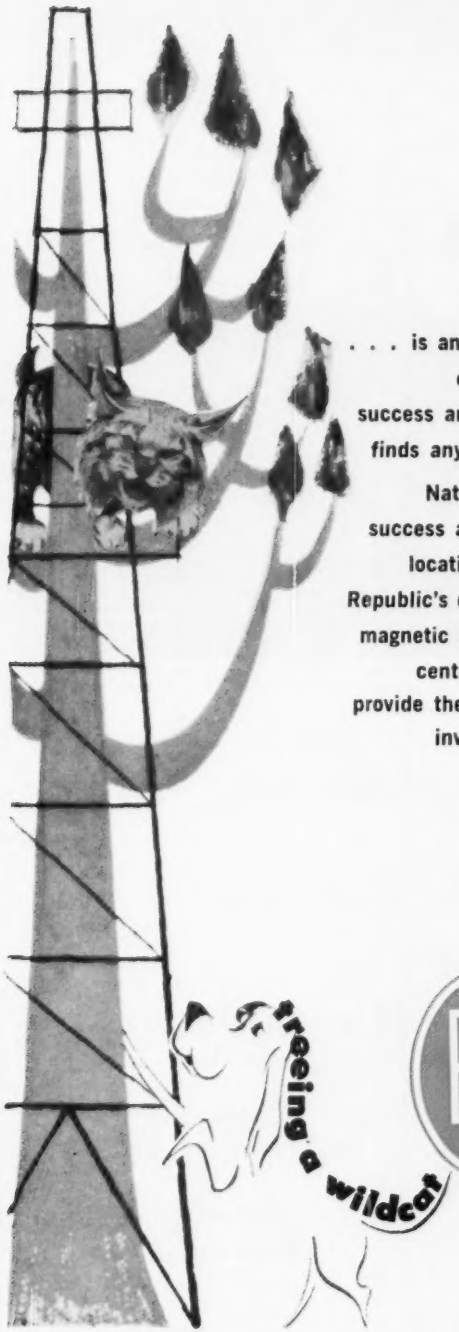
Is now available to any company or individual interested in promoting the objects of the SEG.

MANUFACTURERS, SUPPLIERS and CONTRACTORS who do business with Geophysicists may now enjoy

- IDENTITY WITH THE PROFESSION
- SEG PUBLICATIONS AT MEMBER RATES
- NEWS OF THE PROFESSION

FOR INFORMATION WRITE TO THE BUSINESS MANAGER

SOCIETY OF EXPLORATION GEOPHYSICISTS
Box 1536, Tulsa 1, Oklahoma



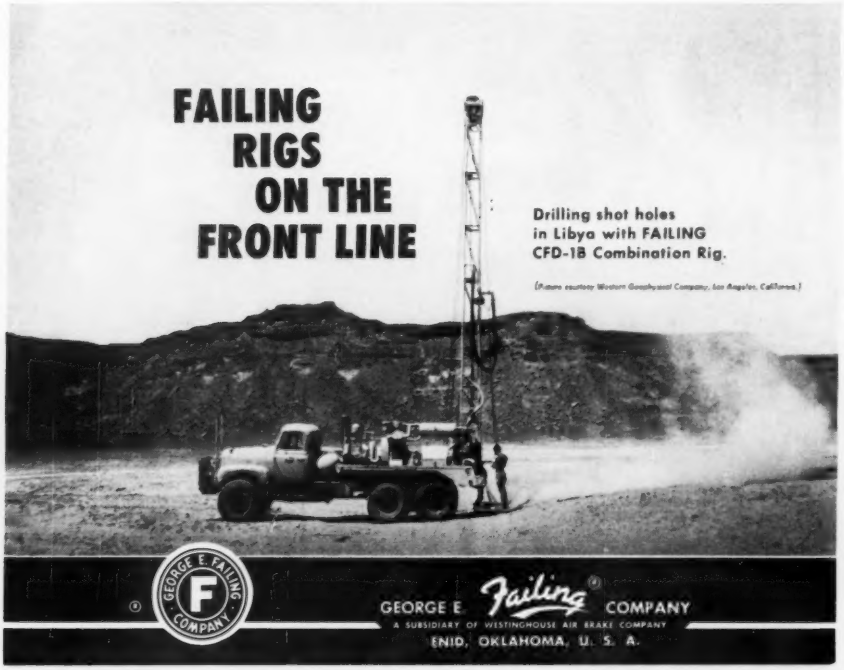
. . . is an expensive and risky business. Return of investment is slow and chances for success are not encouraging — only 1 well in 15 finds any oil and this may not be commercial.

National statistics show your chances for success are three times as good if the wildcat location is based on technical information. Republic's crews, equipped with the most modern magnetic equipment and backed by a complete central office playback system, can better provide the information needed to enhance your investment. Check with Republic before drilling your next wildcat.

Write, Republic, Dept. B, Box 2208, Tulsa, Oklahoma, for your copy of a U. S. Map showing all major geological features.

Rx REPUBLIC EXPLORATION COMPANY

TULSA, OKLAHOMA • MIDLAND, TEXAS



BERT F. DUESING, INC.

"Selling Atlas Explosives"

AND

Manufacturers of Blasting Agents

Magazines and Plant
BIG LAKE, TEXAS

phone
Big Lake 500

Magazines
HASKELL, TEXAS

phone
UNion 4-2456

make your plans . . .

Today!

G A L V E S T O N

November 7-10

Moody Convention Center

•

30th Annual International Meeting

S. E. G.

MAGNETOMETER MAKES 9-MILE SURVEY IN ONE AFTERNOON

Speed is typical of Varian's M-49 portable ground magnetometer. Unlike earlier magnetometers, this revolutionary proton-free-precession instrument measures total field intensity. Hence it requires no leveling, critical orientation or calibration and reads directly in gammas with consistent and accurate repeatability. Freedom from leveling lessens operator fatigue and also provides versatility of use.

This particular survey, done near Mount Diablo State Park in California, included 120 stations. The distance was covered by motor vehicle, but all readings were taken far enough away from the vehicle to eliminate possible error. The survey clearly indicated faults and subsurface geologic features.

The Varian M-49 weighs only 16 pounds. Two miles of traverse per hour can be covered by a man on foot taking readings as often as every twenty paces.

For full information, write the Varian Instrument Division

VARIAN associates
PALO ALTO 29, CALIFORNIA

WILEY TITLES
in geology and mineralogy

FLINT: Glacial and Pleistocene Geology .....553 pp. $12.50

DUNBAR AND RODGERS: Principles of Stratigraphy .....356 pp. $10.00

CHAYES: Petrographic Model Analysis .. ..113 pp. $5.50

SCHUCHERT: Atlas of Paleogeographic Maps of North America ..177 pp. $4.75

BUERGER: Elementary Crystallography: An Introduction to the Fundamental Geometrical Features of Crystals ....528 pp. $8.75

DANA: System of Mineralogy, Seventh Edition, Volume I: Elements, Sulfides, Sulfosalts, Oxides .....834 pp. $14.00
Volume II .....1124 pp. $16.00

MASON: Principles of Geochemistry ....310 pp. $8.50

DANA-HURLBUT: Manual of Mineralogy, Seventeenth Edition .609 pp. $11.50

ABELSON: Researches in Geochemistry . .....511 pp. $11.00

BUERGER: Vector Space: And Its Application in Crystal-structure Investigation .. ..347 pp. $12.00

DAPPLES: Basic Geology for Science and Engineering .....609 pp. $9.50

STIRTON: Time, Life and Man: The Fossil Record .....559 pp. $9.00

ZUMBERGE: Elements of Geology ....382 pp. $5.50

BISHOP: Subsurface Mapping ....198 pp. $5.75

CAROZZI: Microscopic Sedimentary Petrography .....485 pp. $9.50

EMERY: The Sea Off Southern California .....366 pp. $12.50

LANDES: Petroleum Geology, Second Edition .....443 pp. $9.50

SLOSS-DAPPLES-KRUMBEIN: Lithofacies Maps: An Atlas of the U. S. and Southern Canada .....108 pp. $5.50

RILEY: Our Mineral Resources ....338 pp. $6.95

WAHLSTROM: Optical Crystallography, Third Edition .....356 pp. $8.50

For Sale by

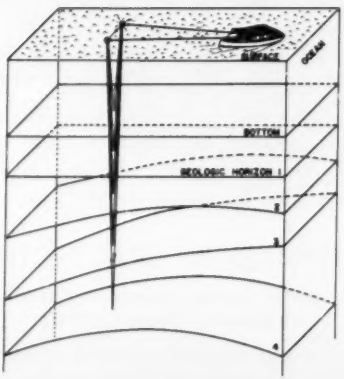
SOCIETY OF EXPLORATION GEOPHYSICISTS
Box 1536, Tulsa 1, Oklahoma

Please mention GEOPHYSICS when answering advertisers

PRECISION RADAR

SPARKER

GAS EXPLODER



Petroleum Exploration Surveys — GAS EXPLODER AND SPARKER

Marine Engineering Surveys — SPARKER

Survey Location Control — PRECISION RADAR NAVIGATION SYSTEM

MARINE GEOPHYSICAL SERVICES CORP.

2418 TANGLEY

HOUSTON 5, TEXAS

Phone — JA 6-4428 Cable — MARGEO

EUROPEAN ASSOCIATION

OF

EXPLORATION GEOPHYSICISTS

The E.A.E.G. was founded in December 1951

The aims of the Association are to promote the science of exploration geophysics by establishing contacts and encouraging co-operation and fellowship between geophysicists in Europe and elsewhere and by disseminating knowledge of the science through the agency of regular meetings and the publication of technical papers.

MEMBERSHIP

Active Members pay an annual membership fee of Neth. fls. 15.—, increased by Neth. fls. 0.50 collecting charges. In U.S. currency this charge amounts to $4.10.

Prospective Members. Anybody interested in geophysics can apply for membership by sending in an Application Form, duly filled out. Forms will gladly be supplied by the Secretary-Treasurer of the E.A.E.G. but may also be obtained through the kind assistance of the Business Manager of the S.E.G.

GEOPHYSICAL PROSPECTING

Official Journal of the European Association of Exploration Geophysicists

This journal is issued quarterly and contains articles written in English, French or German. English, however, is predominant and each article is preceded by an abstract in that language.

Active members receive the journal free of charge.

In accordance with the Terms of Affiliation with the Society of Exploration Geophysicists, members of that Society may enter a current subscription to the journal for the normal membership fee.

The Subscription Rate for non-members is Neth. fls. 22.—(U.S. $5.80) per annum. Single copies are available at Neth. fls. 6.—(U.S. $1.60). These rates include packing and postage and are payable in advance. A limited quantity of previous issues is still available at the same price.

Advertising rates will be sent upon request.

All communications to be directed to:

THE SECRETARY-TREASURER E.A.E.G.

30, C. VAN BYLANDTLAAN • THE HAGUE • NETHERLANDS

GEOPHYSICS

ALL OVER THE WORLD

PRAKLA

HANNOVER · HAARSTRASSE 5 · PHONE: 86661 · TELEX: 922847 · CABLE: PRAKLA

FOUR IMPORTANT NEW BOOKS FROM McGRAW-HILL

IGNEOUS AND METAMORPHIC PETROLOGY, *New Second Edition*
By FRANCIS J. TURNER and JOHN VERHOOGEN, *both of the University of California, Berkeley.* 694 pages. $12.00

As before, the book represents a unified general impression of origin and evolution of rocks that have crystallized, or have been profoundly modified, at high temperatures. It is correlated with modern conceptions as to the nature and prevailing physical conditions of the earth's crust and of the outer part of the underlying mantle. Igneous and metamorphic phenomena have been treated, in a single volume, as partially dependent on each other, and as being controlled by the same general physico-chemical principles.

INTRODUCTION TO GEOPHYSICAL PROSPECTING, *New Second Edition*
By MILTON B. DOBRIN, *Triad Oil Company, Ltd. Calgary, Alberta, Canada.* 446 pages, $9.50.

A thorough revision of a highly successful text. It is designed to present the principles of current techniques of geophysical prospecting for oil and minerals to students and technical personnel employed in the fields of petroleum and mineral exploration. The book covers all the major methods of geophysical prospecting. For each method it discusses fundamental physical principles, instruments, field techniques, reduction of data, interpretation, and examples showing results of actual surveys.

GEOLOGY: Principles and Processes, *New Fifth Edition*
By WILLIAM H. EMMONS. IRA S. ALLISON, *Oregon State College;* GEORGE A. THIEL, *University of Minnesota;* and CLINTON R. STAUFFER, *California Institute of Technology.* 491 pages, $7.95.

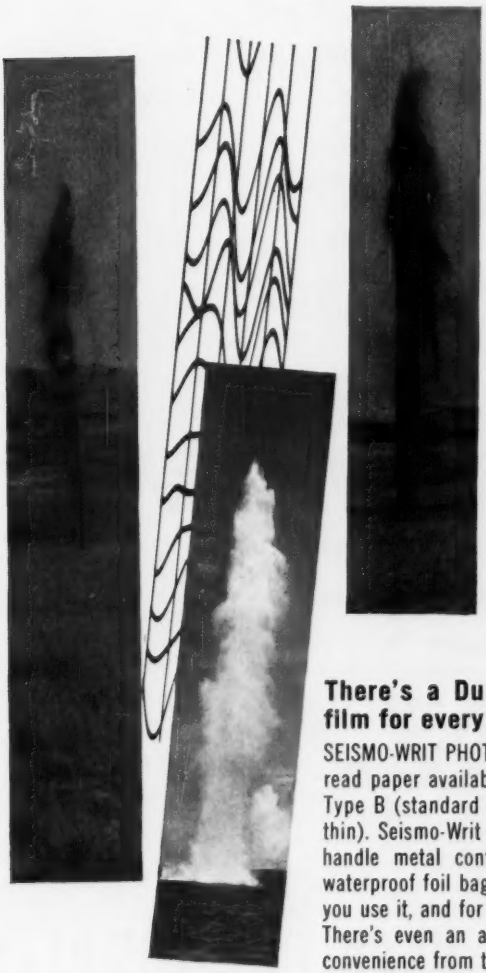
A textbook for a beginning one-semester course in Physical Geology. It has been a standard and leading text for this field for over 27 years. This new fifth edition has been the most extensive of all its revisions. It is receiving special editing treatment and the result will be a completely rewritten text, with entirely new art work done by a professional scientific illustrator, and a skilled use of two colors throughout. The text is suitable for both terminal cultural courses, or for introductory courses for majors in the subject.

PRINCIPLES OF PETROLEUM GEOLOGY, *New Second Edition*
By WILLIAM L. RUSSELL, *Agricultural and Mechanical College of Texas.* 503 pages, $9.50.

This new edition of one of the most important books in this area has been carefully revised; much new material has been added, and all other information has been brought fully up to date. The first 17 chapters deal with principles; the remaining 12 chapters cover the specialized methods or techniques used by petroleum geologists. The book will be of value, therefore, not only to students, but also to those involved in the oil industry.

Send for Copies on Approval

McGRAW-HILL BOOK COMPANY, INC.
330 West 42nd Street New York 36, N. Y.



better traces every time... on Du Pont's seismic papers and films

There's a Du Pont seismic paper and film for every job:

SEISMO-WRIT PHOTORECORDING PAPER. Fast, easy-to-read paper available in standard sizes and in either Type B (standard weight) or Type W (all-rag, extra-thin). Seismo-Writ comes in strong, durable, easy-to-handle metal containers. All rolls are supplied in waterproof foil bags for safe storage of paper before you use it, and for your traces after the shot is made. There's even an address label provided for mailing convenience from the field.

CRONAR* RECORDING FILM. Relative speed (tungsten) 30.

LINO-FLEX 1. Relative speed (tungsten) 10.

Both of these films are on Du Pont's tried and proven CRONAR* polyester photographic film base, which offers unexcelled strength, exceptional dimensional stability and flexibility, rapid drying.

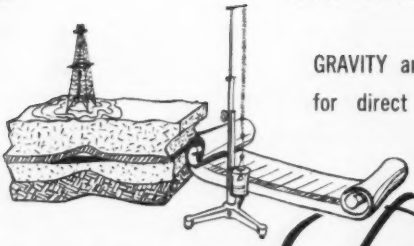
For more information on our seismic line of paper, films and chemicals, write: E. I. du Pont de Nemours & Co. (Inc.), Photo Products Department, Wilmington 98, Delaware. In Canada: Du Pont of Canada Limited, Toronto.

DU PONT

REG. U.S. PAT. OFF.

Better Things for Better Living
... through Chemistry

*Du Pont's trademark for its polyester photographic films
This advertisement was prepared exclusively by Phototypography



GRAVITY and MAGNETIC SURVEYS and INTERPRETATIONS for direct correlation with subsurface conditions by preparation of **Density Logs** and **Differential Residuals.**

PHONE CApitol 2-6266
1045 ESPERSON BUILDING
HOUSTON 2, TEXAS

Bible **GEOPHYSICAL CO., INC.**
JOHN L. BIBLE, President

TROJAN EPCO

TROJAN PLUGS
SURE GRIP TAMPS
DYNA-POINTS
DYNA PUNCHES
& KNIVES

EXPLORATION PRODUCTS COMPANY
500 W. Main St. -- Phone 6234 - Nite 2-5150 -- Box 445 -- Palestine, Texas

F-71 STEREO VIEWER
FOR OBTAINING STEREO DETAIL
FROM AERIAL PHOTOS

Designed for stereoscopic viewing of overlapping stereo pairs of aerial photographs. Vacuum coated silicon monoxide mirrors. Hi-grade prisms and mirrors. BRAND-NEW

24.50 FOB N.Y.

APPROVED U.S. GOV'T FOR MILITARY

AIR PHOTO SUPPLY CORP. Dept. E-4 555 E. Tremont Ave. New York 57, New York

Hot ship plays it cool *on desert explorations. The 305 hp Hiller 12 E is as untroubled by wind-blown sand as a well-built truck; as powerful as the biggest bulldozer. When you put a 12 E to work in the desert, it often carries the same seismic crew and gear on one flight that other copters could transport only in two or more.*

The Hiller has ***proved*** *in commercial service that it operates effectively and economically under full load at high altitude and at any latitude. It can even carry the fuel for* ***six hours' cruise*** *with profitable payload remaining. It's this margin of power that could be vital to your operation.*

All this and more reasons, too. Your Hiller 12 E operator will demonstrate them to you—show you why more and more charter contracts specify ***Hiller 12 E.*** *Write for booklet, "New Workhorse for Petroleum." It gives full information on the 12 E and on Hiller charter operators' trip or contract services everywhere. Address Commercial Division*

HILLER
AIRCRAFT
CORPORATION
PALO ALTO, CALIFORNIA

HS-J

SUB-MINIATURE GEOPHONE

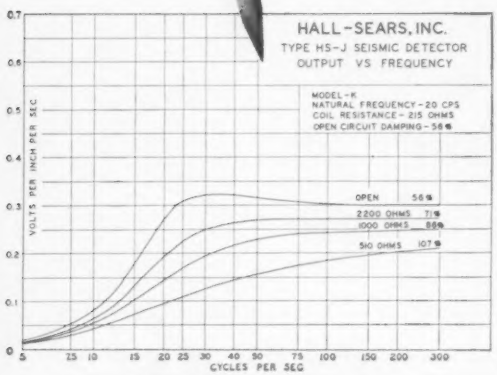
Newest Star in the H-S Line

HS-J
Actual size

Because of its extremely small size and handling ease, the HS-J opens the way to more efficient field operations with drastically reduced personnel and equipment requirements.

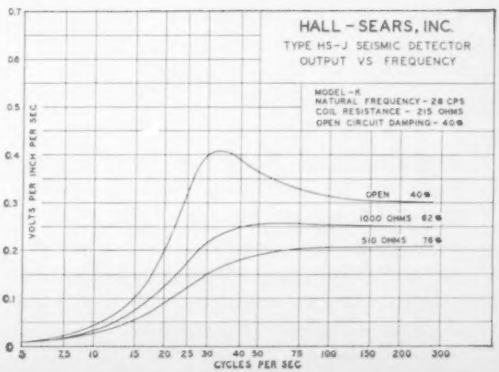
In its compact package, this new geophone gives a remarkable performance, equalling that of other larger conventional, single coil types. Its high output is accomplished without sacrificing rugged construction, permitting the use of mechanical cable handling equipment and other time-saving, yet abusive, field techniques without damage. The HS-J is free from spurious resonances.

Run your own tests with the HS-J. Hall-Sears will be glad to furnish trial quantities without cost or obligation.



SPECIFICATIONS

Standard frequencies: 14-30 cps
Standard impedance: 215 ohms
(Other impedances available)
Basic unit
Height: 1.1"
Diameter: .875"
Weight: 2 oz.



ACCESSORIES

A full line of attachments is available for land and marine applications.

GUARANTEE

The HS-J carries a full two-year guarantee against all hazards except burnout from external voltages.

HALL-SEARS, INC.
2424 BRANARD • HOUSTON, TEXAS, U.S.A.
Phone: JAckson 6-2975 • Cable Address: HALSEA

WORLD WISE IN SEISMIC INSTRUMENTATION

HALL-SEARS INTERNATIONAL
2424 Branard, Houston, Texas
Cable Address: HALSEA
European Branch Banstraat 2, The Hague, Holland

HALL-SEARS EUROPA, N.V.
Banstraat 2, The Hague, Holland
Cable Address: HALSEA

HALL-SEARS FRANCE, S.A.
82 Haussmann, Paris VIII eme, France
Cable Address: HALSEA

SEISMIC INSTRUMENTS LIMITED
Durham Road, Boreham Wood, Herts, England
Cable Address: SEISMIC

HALL-SEARS ALBERTA, LTD.
119 63rd Avenue, S.E.
Calgary, Alberta, Canada

SSC HAS WHAT IT TAKES TO FIND OIL . . . ANYWHERE!

Modern Field Equipment, Experienced Field Crews, for Economical Prospecting

Seismic Replay Center for More Informative Interpretations

Magnetic Tape Conversion for Greater Versatility in Exploration

Data Plotting for More Realistic Data Presentation

Management with World-Wide Experience and Background for Reliable Results

Seismic Recording Instruments for Effective Prospecting

Analog Computing for More Significant Gravity Surveys

WORLD-WIDE EXPERIENCE ON ALL CONTINENTS

Seiscor Manufacturing Company Division — Integrated Engineering and Manufacturing

Birdwell Division Complete Wireline Services — When & Where Needed

THESE SERVICES AVAILABLE FOR YOUR USE NOW

CALL OR WRITE . . .

SEISMIC — GRAVITY AND MAGNETIC SURVEYS — LORAC — CONTINUOUS VELOCITY LOGGING

Seismograph Service Corporation

P. O. Box 1590 • TULSA, OKLAHOMA • Riverside 3-1381

WORLD-WIDE SUBSIDIARIES

SSC of Argentina • SSC of Bolivia • SSC of Canada • SSC of Colombia • SSC International • SSC of Libya • SSC of Mexico SSC of Venezuela • Seismograph Service Limited—England • Seismograph Service Nations Compagnie Francaise de Prospection Sismique

On the surface, tellurometers accurate to within inches over a fifty-mile traverse are visible indicators of GSI's new look at refraction shooting.

Looking deeper, recently developed refraction interpretation techniques, special refraction instruments and seismometers are giving GSI clients subsurface data in areas where it was unobtainable in the past.

If you have prospects which refuse to yield deep data through the use of reflection shooting our new look at refraction will interest you.

For additional details, write ....

GEOPHYSICAL SERVICE INC.

A TEXAS INSTRUMENTS COMPANY

900 EXCHANGE BANK BLDG. • DALLAS 35, TEXAS